The Role of Mental Representations of Order in Mathematical Cognition: A Developmental Approach

O'Connor, Patrick A.

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The Role of Mental Representations of Order in Mathematical Cognition: A Developmental Approach

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Patrick Aaron O'Connor, BSc (Hons)

Supervisors: Dr. Kinga Morsanyi and Prof. Teresa McCormack

Abstract

Many authors have focused on the importance of magnitude in the development of mathematical abilities. However, given that ordinality is also an important aspect of number, there are now several studies which have shown that numerical ordering abilities are also important to mathematical development, although relatively few developmental studies have considered the contribution of non-numerical ordering skills, and most have not considered the importance of ordering skills involving ordinal sequences that are familiar to even very young children, such as the order of familiar everyday tasks and familiar daily events.

The current thesis attempted to address the question of whether order-processing skills were predictive of maths achievement during the foundation years (between the ages of 4-6) and during Key Stage 2 (between the ages of 8-11). Since the school starting age of children in Northern Ireland is the youngest in Europe, the current thesis provides an insight into skills that are important for maths learning amongst very young children at the beginning of primary school, as well as amongst children who are preparing to leave primary school.

The findings of the empirical chapters in this thesis support the importance of numerical and non-numerical ordering skills across childhood. The novel finding was that non-numerical ordering skills, involving the ordering of familiar content, were shown to be important to early maths learning. Furthermore, order-processing skills were also shown to be involved in the development of mathematical and reading skills

amongst older children, showing that order- processing skills may also be involved in other academic subjects.

The findings of the current thesis suggest that order-processing skills are important to mathematical development across childhood. Ordering skills, involving the ordering of familiar content, may be a suitable candidate for the creation of diagnostic tools to identify children with mathematical difficulties at an early stage, as well as providing the basis for a mathematical intervention. Further research into order-processing skills may involve assessing exactly how these skills they are related to reading development, investigating whether ordering skills are linked to other cognitive disorders (such as Gerstmann's syndrome), as well as assessing whether order-processing skills are also linked to maths achievement in children educated via non-mainstream educational pedagogies, such as the Steiner-Waldorf and Montessori pedagogies.

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Table of Contents

Chapter 3: The role of numerical and non-numerical ordering skills to maths development at the beginning of formal education

Chapter 4: The role of numerical and non-numerical ordering skills in maths development among 8-11 year-old children

Chapter 5: Discussion

List of figures and tables

Chapter 1: The role of domain-general and domain-specific predictors of mathematics amongst primary school-age children

1.0 General introduction

The purpose of this thesis was to investigate the role of ordering abilities in the development of maths skills throughout the primary school years, with three key aims; to investigate the role of numerical and non-numerical ordering abilities in numerical development; to track developmental changes in the relationship between ordering abilities and maths; to investigate the underlying mental representations and the relations between different types of ordering tasks.

In Section 1.1, I discuss maths learning in the context of Northern Ireland. In section 1.2, I discuss the literature in support of the role of domain-specific precursors (magnitude and estimation) in numerical development, and the evidence supporting an underlying system which is responsible for the processing of non-symbolic magnitude. I also review the literature concerning some of the tasks used to measure magnitude and estimation skills. Section 1.3 contains a discussion of the literature concerning domain-general precursors of maths, with respect to the role of Executive Functions and Working memory. Section 1.4 highlights the issues that are to be addressed throughout the thesis, whilst section 1.5 provides a summary of the first chapter and an outline of the subsequent chapters.

1.1 Mathematics learning in Northern Ireland

According to the Council for the Curriculum, Examinations and Assessment (2016), the Northern Ireland mathematics curriculum places an emphasis on teaching children how to apply mathematical skills in everyday contexts, so that children can apply these skills to everyday situations later in life. The statutory requirements for maths learning during the Foundation years (between the ages of four and six) and for Key Stages 1 (between the ages of six and eight) & 2 (between the ages of eight and 11), are outlined in Table 1.1.

Table 1.1. Table outlining the statutory requirements for maths learning in Foundation, Key Stage 1 and Key Stage 2 in Northern Ireland

Foundation (4-6 y/o)	**KS1 (6-8 y/o)**	**KS2 (8-11 y/o)**
Understanding number	Processes in mathematics	Processes in mathematics
Counting & number recognition	Number	Number
Understanding money	Measures	Measures
Measures	Shape & space	Shape & space
Shape & space	Handing data	Handing data
Sorting		
Patterns & relationships		

However, despite the implementation of initiatives aimed at improving basic skills in school-age children in Northern Ireland (Department of Education, 2011), many children fail to achieve key targets in numeracy and literacy at each Key Stage of education. One report (Northern Ireland Audit Office, 2006) found that 5% of children were not achieving the expected level for numeracy and literacy at Key Stage 1; 23% of children were not achieving the expected level at Key stage 2 and 40% of children were not achieving the expected level at Key Stage 3 (aged between 11-14), suggesting that there are still a large number of children who are failing to meet the required standard at different developmental stages, and that these percentages seem to increase as children get older.

Those children who fail to meet these numeracy and literacy targets may be at risk of entering adolescence and adulthood with poor numeracy and literacy skills. This is quite concerning, given that poor literacy and numeracy skills have been linked to several negative outcomes, such as being less likely to remain in education and earning less wages in future employment, compared to individuals with good literacy and numeracy skills (Northern Ireland Audit Office, 2009). Indeed, it is noteworthy that adults in Northern Ireland have below-average numeracy skills, in comparison to adults from many other European countries (Organisation for Economic Co-operation and Development, 2013). Furthermore, adults in Northern Ireland, who possess poor basic numeracy skills, are much more likely to be unemployed; to be dependent upon state benefits; are more susceptible to suffering from depression and/or ill-health, and are more likely to be living in poorer-standard housing (Northern Ireland Audit Office, 2009). Lower numeracy levels amongst adults are also associated with several factors such as lower education, lower parental education, unemployment and no regular experience of using computers in daily life (Department for Employment and Learning in Northern Ireland, 2012). Intervention at the Governmental level should be of upmost importance, since it is estimated that poor numeracy skills cost the UK government around £20bn per year (Pro Bono Economics, 2014). These reports suggest that the negative effects of poor numeracy skills have more far-reaching consequences outside of the classroom, and that maths difficulties in childhood may negatively impact on individual's future educational and career choices.

These reports highlight the importance of detecting academic problems at the earliest possible stage, as perhaps these issues can be addressed before they exacerbate. Therefore, one of the goals of mathematical cognition research should be to identify key skills, at the earliest possible stage, which may be pivotal in scaffolding children's early numerical development, to address the problematic areas before they get worse. It should also be important to identify the important skills for numerical development amongst older children, who are preparing to leave primary school, to ensure that these children are well-equipped for the rigours of more complex maths learning in secondary school. An understanding of these important early skills could then form the basis of diagnostic tools and interventions aimed at identifying children who are at risk of falling behind, and providing them with training to help these children to catch-up with their peers, allowing them to reach the expected attainment level at each of the key stages.

1.1.1 The contribution of the study of the development of numerical abilities in primary-school age children

An important issue that runs throughout this thesis concerns how many studies of early mathematical development in European countries, such as Belgium and the Netherlands (e.g., Attout & Majerus, 2018; Attout, Nöel & Majerus, 2014; Lyons et al. 2014), have involved children who begin formal education at age six, the same age that American, Canadian, Japanese and Chinese children begin school (InterNations, 2018; Just Landed; 2018a, 2018b; Tokyo International Communication Committee, 2006). However, children in Northern Ireland have the youngest school starting age in Europe, and one of the youngest school starting ages in the world, as these children begin school at aged four (Eurydice at NFER, 2013). In the rest of the UK, children begin school a year later (see Table 1.2).

Table 1.2. Table showing the school starting age (in years) for selected European, North American and Asian countries

Northern Ireland	**England Scotland Wales**	**France Belgium Netherlands**	**USA Canada**	**China Japan**
4 years old	5 years old	6 years old	6 years old	6 years old

Claims made by other authors regarding the skills that are important to early maths learning may, therefore, be influenced by the differences in chronological age when children begin school in different countries, as there are also differences between countries in terms of how much time children spend learning at home with their parents. Children in Northern Ireland typically attend Nursery for 1 year, at the age of 2-3, before starting Primary school in the first September after their 4th birthday. Therefore, these factors may have some influence over the extent to which particular skills influence early maths learning.

To test which skills are important to early maths development, Chapter 3 outlines a longitudinal study involving children in Northern Ireland, who were tested between the ages of 4 and 6 with children, to assess the contribution of different skills to maths learning in the first two years of primary school; to track the development of these skills over a two-year period, as well as investigating which measures predicted variance in children's maths achievement at the end of each school year.

According to the Northern Ireland Audit Office (2006), the percentage of children not reaching the required standard in literacy and numeracy at each Key stage appears to increase with age. By Key Stage 2, almost a quarter of children are not reaching the required level, compared to 5% in Key Stage 1, suggesting that an increasing number of children are falling behind in both numeracy and literacy compared to their peers, which is worrying considering that children in Key Stage 2 are preparing to finish primary school and to move on to their respective secondary schools. To investigate which skills were important to maths learning amongst older children, Chapter 4 outlines a cross-sectional study involving children aged 8-11, designed to assess which numerical and non-numerical skills were important to maths achievement (and reading skills) at this later stage of development.

The aim of the empirical work in this thesis was to assess the contribution of magnitude and ordinality, both in the early acquisition of numerical skills, as well as in the development of mathematical abilities amongst older children, given that both of these skills are considered to be important to counting (Gelman & Gallistel, 1978), and to maths learning in general (Lyons & Beilock, 2011). The importance of this investigation was to determine the relative importance of these skills in children's maths learning across primary school. These results could provide useful evidence for educational organisations, such as the Education Authority in Northern Ireland, regarding the creation of diagnostic tools for detecting potential maths difficulties at the earliest possible stage, as well as assisting in the creation of interventions aimed at improving maths skills amongst those who are at risk of falling behind in terms of maths learning.

1.2. Magnitude

Children's acquisition of knowledge about magnitude involves learning that specific quantities of items can be referred to using symbolic number words (Geary, 2013; Siegler & Lortie-Forgues, 2014), and it has been proposed by some authors that knowledge about the magnitude of numbers within the number system emerges earlier than knowledge about the order of the numbers within the number system (e.g. Colomé & Nöel, 2012; Wiese, 2007), suggesting that magnitude processing is an important skill in the early development of symbolic number knowledge, which underlies much of later maths learning in school.

Magnitude-processing skills may be initially built upon children's ability to judge the magnitude of small sets of items. Le Corre & Carey

(2007) proposed that young children learn to map the number words from 1-4 onto their represented quantities through subitizing; the ability to make fast and accurate judgments about small sets of 1-4 items, compared to larger sets of 5 items and above (Kaufman, Reese & Volkmann, 1949). Some authors (e.g. Le Corre and Carey, 2007; Spaepen et al., 2018) suggest that it is only once children learn to effectively subitize, that they are able to acquire the other counting principles, as set out by Gelman and Gallistel (1978). These principles are; (1) *The one-on-one principle* (one count word is assigned to each item to be counted); (2) *The stable-order principle* (the count words are to be used in the same particular order); (3) *The cardinal principle* (the final word used in a counting sequence represents the cardinal value of the items that have just been counted); (4) *The abstraction principle* (the previous principles can be applied to the counting of any set of objects), and (5) *The order-irrelevance principle* (it makes no difference in which order items are counted, as long as only one count word is used per item). Le Corre and Carey (2007) argue that, six months after they acquire these counting principles, children learn to extend their counting range beyond the numbers within the subitizing range by mapping the number words onto analog magnitudes (although see Davidson, Eng & Barner, 2012).

Before children begin to develop symbolic number skills, they already possess some rudimentary representations of magnitude that are based on the representation of sets of items. Some authors (e.g., Dehaene, 1997) have argued that we are born with an innate ‘number sense’, which acts as a scaffold for the development of symbolic number skills. Of interest to researchers has been to what extent is children's ability to represent non-symbolic magnitude (which reflects an innate number sense) related to their symbolic arithmetical performance, as well as investigating whether the processing of both symbolic and non-symbolic magnitude is related. If the latter proposal is true, then this would suggest that they draw on the same underlying processes, providing further support for the prediction that these approximate, non-symbolic skills may be important to the development of symbolic number skills and subsequently, the development of mathematical abilities. However, others (e.g., Feigenson, Dehaene & Spelke, 2004) argue that we possess two separate systems for representing number; an approximate system that is imprecise (see section 1.2.1) and a precise system for representing small quantities of objects. In this respect, it could be argued that the processing of symbolic and non-symbolic magnitude is unrelated, and therefore number sense may not be an important factor in the development of mathematical skills. This debate will be discussed further in this chapter.

In the following sections, I will review the literature on the role of symbolic and non-symbolic magnitude in numerical development, as well as the extent to which symbolic and non-symbolic tasks are related to mathematical skills, and to each other.

1.2.1 The Approximate Number System (ANS)

It has been suggested that both humans and non-humans share a rudimentary and evolutionarily ancient sense of magnitude, allowing for the mental representation and manipulation of non-symbolic magnitude that does not rely on the development of language skills (Cantlon & Brannon, 2007; McCrink & Wynn, 2004; Starkey & Cooper, 1980; Xu & Spelke, 2000). This system has been referred to as the '*Approximate Number System*' (ANS; Piazza et al., 2010) or 'number sense' (Dehaene, 1997).

The ANS generates an approximate mental representation of quantity and, according to Dehaene (1997), approximate analogue magnitude representations of numbers are represented along a continuum (known as the mental number line), from left to right in Western cultures, and in increasing magnitude, with smaller numbers represented spatially on the left and larger numbers spatially represented on the right of this number line (this is reversed in cultures which employ a right-to-left writing system).

Dehaene (1997) proposed that children's representation of smaller numbers on this mental number line is somewhat precise, but as the magnitude of the number increases, the underlying representations become fuzzier and more imprecise (the numerical size effect; e.g., Halberda, Mazzocco & Feigenson, 2008). This effect occurs as quantities are represented by the ANS as noisy, overlapping Gaussian distributions along a mental number line (Piazza, Izard, Pinel, Le Bihan & Dehaene, 2004), and there is more overlap between larger numbers on the mental number line compared to smaller numbers, making judgements about numerosity more difficult when the quantities to be compared are larger, compared to when they are smaller, even when the numerical distance between the numbers is the same (e.g., comparing 8 & 9 is more difficult than comparing 2 & 3).

Approximate representations of magnitude follow Weber's law, in that the ability to discriminate between two approximate quantities becomes more difficult as the numerical ratio/distance between the quantities approaches one. As a result, performance on magnitude comparison tasks often show a numerical ratio/distance effect, in tasks in which counting or exact calculation is prevented (Lourenco, Bonny, Fernandez & Rao, 2012). These effects are thought to arise from noisy mapping between representations of magnitude, with magnitudes that are closer together on the mental number line sharing more representational characteristics compared to quantities that are further apart, thus making them harder to distinguish (e.g., Holloway & Ansari, 2008). Together, both size and distance/ratio effects are thought to provide support for Dehaene's (1997) account of magnitude being represented approximately along a horizontal mental number line, which increases in magnitude from right to left in Western cultures.

1.2.2 Mapping between the ANS and symbolic numbers

The issue of how non-symbolic magnitude becomes associated with the numerical symbols that they represent (in other words, how do numerical symbols acquire semantic meaning) has been referred to as the 'symbol-grounding' problem (e.g., Leibovich & Ansari, 2016; Reynvoet & Sasanguie, 2016). This has been investigated by assessing the extent to which performance on symbolic and non-symbolic magnitude tasks are related. Evidence of a relationship implies that the processing of magnitude may share similar cognitive mechanisms, suggesting that the ANS may be involved in the step between approximate and exact symbolic knowledge. However, evidence of no relationship between the two suggests that the systems responsible for symbolic and non-symbolic processing are distinct, which would question the role of the ANS as a precursor to symbolic number knowledge acquisition.

One suggestion in favour of common mechanisms underlying symbolic and non-symbolic magnitude processing is that the ANS allows children to map numerical symbols onto non-symbolic representations of quantity (Lipton & Spelke, 2005), and is thought that, through this mapping process, children develop their knowledge of the symbolic number system which underlies mathematics. There is some research support for non-symbolic mapping skills as a precursor to symbolic number knowledge during the early years of schooling. Wong, Ho & Tang (2016) found that six-year-old's mapping ability (measured by Numerosity naming, Numerosity production & Number line estimation) fully mediated the relationship between the ANS (measured by Non-symbolic tasks involving; comparison; addition; subtraction and multiplication) and arithmetic performance. No significant direct effect was found between the ANS and arithmetic. Odic, Le Corre & Halberda (2015) found that children could map numbers to underlying ANS representations before the age of four (in a task in which children made a verbal response to an approximate quantity), but did not show the reverse mapping ability until after age 4 (in a task in which children had to tap rapidly in response to a number word). Furthermore, Mundy and Gilmore (2009) found that both 6-year-old and 8-year-old children could map bi-directionally (mapping a non-symbolic quantity to a symbol and vice-versa) and that this ability improved with age. These studies suggest that from an early age, mapping skills play an important role in the development of numerical abilities, supporting the evidence which suggests a role for the ANS in early symbolic number knowledge acquisition.

However, there is strong evidence to suggest that the mapping account of numerical development fails to sufficiently answer the symbol-grounding problem (e.g., Leibovich & Ansari, 2016; Reynvoet & Sasanguie, 2016; Torbeyens, Gilmore & Vershaffel, 2015). As previously mentioned, Feigenson et al. (2004) argue in support of a model that involves two separate systems for approximate and exact numerical processing, which would cast doubt over the role of the ANS in mathematical development. For example, Kolkman, Kroesbergen and Leseman (2013) investigated the relationship between symbolic skills (Number naming, Counting), non-symbolic skills (Non-symbolic number line, Non-symbolic comparison) and mapping abilities (Symbolic number line, Symbolic comparison) in a longitudinal study of children at age 4, 5 and 6. Using confirmatory factor analysis, Kolkman and colleagues found that these three skills loaded on three separate factors at age 4 and 5, and loaded on a single factor at age 6. Early non-symbolic skills did not predict later mapping or symbolic skills, whilst early symbolic skills predicted both non-symbolic and mapping skills. Furthermore, only the symbolic mapping tasks at age 5 were predictive of both maths achievement and numerical skills, which further casts doubt upon the prediction that non-symbolic skills are the foundation of symbolic skills during the early years. Matejko and Ansari (2016) longitudinally investigated both symbolic and non-symbolic comparison skills with children at the beginning, middle and end of grade 1. Children performed significantly better on the Non-symbolic comparison task than the Symbolic comparison task, at the beginning and at the middle of first grade, there was no significant difference in performance on the two tasks at the end of grade 1. The children also showed a significantly greater increase in symbolic comparison performance over time, compared to non-symbolic comparison. Furthermore, the authors found that symbolic comparison skills (and not non-symbolic comparison) in the first half of the school year predicted symbolic skills in the second half of the year, which casts doubt upon the assumption that the ANS is strongly involved in early numerical development.

Two reviews also conclude that the mapping account is insufficient in explaining the acquisition of symbolic number knowledge. Leibovich and Ansari (2016) argue that research evidence fails to demonstrate strong associations between symbolic and non-symbolic magnitude measures. Furthermore, Reynvoet and Sasanguie (2016) found that the evidence in support of the mapping account was questionable. They also provide an alternative model to the ANS mapping hypothesis, based on symbol-symbol relations; in this model, Reynvoet and Sasanguie suggest that smaller number words in the number system are mapped onto a precise representation of number, which is then combined with children's increasing knowledge about the order of the numbers in the counting system, which results in the development of an exact number system that is based on order relations between the numbers. Their proposal echoes that of

Nieder (2009), who argued that magnitude is important in children's initial representation of number, but that children's later symbolic representations of number are largely governed by the understanding of the order relations between numbers.

The evidence largely fails to support the prediction that the development of symbolic number knowledge is rooted in the ANS, therefore it could be plausible that the system for representing approximate magnitude has nothing to do with the system for exact quantity and, as such, the ANS may not be as strongly involved in early numerical development as was previously thought.

In the following sections, I will review the literature on the role of symbolic and non-symbolic magnitude measures, in terms of their relationship with each other and with maths achievement. I will also discuss the link between performance on the number line estimation task and mathematical development, which has gathered considerable research support.

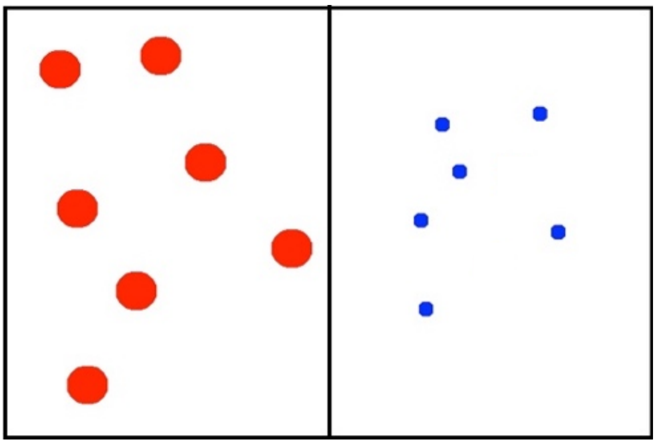

Figure 1.1. Example of a congruent trial (in which dot and area size is positively correlated with numerosity) from the non-symbolic comparison task

1.2.3 Non-Symbolic magnitude

The non-symbolic comparison task (see Figure 1.1) is arguably the most widely used measure of the precision of ANS representations of quantity (also referred to as ANS acuity; e.g., Libertus, Feigenson & Halberda, 2011). In this task, participants must compare two arrays of items (which can be presented simultaneously or sequentially) and make a judgement as to which array contains the most items.

Although performance on this task has been found by many researchers to be related to maths achievement (e.g., Bonny & Lourenco, 2013; Halberda, Mazzocco & Feigenson, 2008; Halberda, Wilmer, Naiman & Germaine, 2012; Libertus, Feigenson & Halberda, 2011, 2013; Libertus, Odic & Halberda, 2012; Lourenco, Bonny, Fernandez & Rao, 2012; Mazzocco, Feigenson & Halberda, 2011; Mundy & Gilmore, 2009; Nosworthy, Budgen, Archibald, Evans & Ansari, 2013), suggesting that these skills may be involved in the development of mathematical skills, there are three main issues which question the importance of the role played by the ANS in numerical development ; a) there are several issues regarding the reliability and validity of the task, despite its extensive use in the literature; b) the results of recent meta-analyses (which have reviewed many studies which have used this task as an ANS measure) suggest that the ANS is a weaker predictor of maths than symbolic magnitude, and c) symbolic and non-symbolic magnitude measures have often been found to be unrelated, suggesting that the ANS may not be strongly involved in the acquisition of symbolic number knowledge. These issues will be discussed in the following subsections.

1.2.3.1 Issues surrounding the Non-symbolic comparison task

One of the main issues with the Non-symbolic comparison task is that there is no single, standardized version of the task. Consequently, different studies control for different visual characteristics (e.g. the size of the items, the size of the perimeter of the array of items); use different methods of stimuli presentation (e.g. simultaneous, sequential or intermixed) and present the stimuli for differing durations.

Furthermore, individual differences in task performance may at least partly depend on participants' ability to ignore visual characteristics and to make judgements solely based on numerosity, which raises the issue of whether the dot comparison is a 'pure' measure of the ANS, or whether it also involves other skills, such as inhibition (Clayton & Gilmore, 2015; Clayton, Gilmore & Inglis, 2015; Gilmore et al., 2013; Gilmore, Cragg, Hogan & Inglis, 2016). Gilmore et al. (2013) found that the relationship between task performance and maths achievement was driven by performance on incongruent trials (trials in which the physical size of the dots are negatively correlated with numerosity), and that this relationship disappeared after controlling for inhibition skills, suggesting that performance on those trials, which are linked to maths achievement, is mediated by the extent to which participants can inhibit irrelevant information in order to arrive at the correct solution. This would suggest that perhaps this task is not an adequately valid measure of the ANS.

A further issue is that there is no single index of task performance. There are several indices of performance on this task (such as percentage accuracy, error rates, reaction times, accuracy/reaction time composites, size of the numerical distance effect), and as a result, may studies have measured performance in different ways (e.g. De Smedt, Noël, Gilmore, & Ansari, 2013). One of the most widely-used indexes of ANS acuity is the Weber *w* fraction (Pica, Lemer, Izard, & Dehaene, 2004), which represents the best approximation of the pattern of errors in task performance, as a function of the ratio between the two dot arrays, with a smaller *w* value indicating better ANS acuity and therefore more precise approximate magnitude representations (Lyons & Beilock, 2011). However, Inglis and Gilmore (2013) argued that comparison of Weber fractions across studies is difficult due to differences in stimuli duration between studies, as the authors found that ANS precision increased as a function of increased stimuli display duration, suggesting that the lack of consistent results in studies which have used this task may be partly due to the variety of ways in which performance on this task has been measured in this task.

The reliability and validity of the dot comparison task has also been questioned (e.g., Inglis & Gilmore, 2013, 2014; Maloney et al., 2010; Price, Palmer, Battista and Ansari, 2012). Price et al. found that there were differences in the strength of the ratio effect depending on stimulus presentation (simultaneous, sequential or intermixed) and how performance was indexed (reaction time, ratio effect, slope steepness or Weber fraction);

all presentation formats generally showed good reliability and validity, whilst both reliability and validity were found to be higher for the Weber fraction. However, there was no significant correlation between either of the performance indexes and maths achievement. Inglis and Gilmore (2014) found better test-retest reliability for accuracy, compared to the Weber fraction, whilst they argued against the use of ratio effect indices as they were found to be unreliable, particularly in developmental studies. Furthermore, another study found higher reliability for Non-symbolic comparison, compared to Symbolic comparison tasks (Maloney et al, 2010). These studies support the argument of De Smedt et al. (2013) by showing that different versions of the task produce varying results, and that there is a lack of agreement as to which index of performance is the most reliable and valid one to use.

The issues surrounding the Non-symbolic comparison task suggest that perhaps this task is not an adequate measure of the ANS (in section 1.2.3.2, I outline another ANS task which has been used in the literature). Due to the lack of a standardized measure in the literature, studies have indexed performance using an array of different measures and have controlled for different continuous variables in the task. Furthermore, there is evidence to suggest that this task may be measuring other skills (e.g., Executive Functioning), and thus may not be a pure measure of the ANS. Given these findings, it is perhaps uncertain as to how much one can interpret the results of studies which have used this task. For these reasons, I did not include this task as a measure of non-symbolic magnitude-processing skills with younger children, instead I used the Non-symbolic addition task (outlined in the following subsection). However, I did include a version of the Non-symbolic comparison task (using quantities between 1-9) it in the study with older children, as I wished to use the exact same trials for both this task and the Number comparison task, and also given that performance on the Small comparison task has previously been found to be correlated with performance on the Non-symbolic addition task (Gilmore, Attridge, De Smedt & Inglis, 2014).

1.2.3.2 An alternative ANS task; Non-symbolic addition

The Non-symbolic addition task (e.g., Barth, Beckmann & Spelke, 2008; Barth, La Mont, Lipton & Spelke, 2005; Gilmore, McCarthy & Spelke, 2010) involves the presentation of two 'sum' arrays of dots, the sum of which must be compared to a third 'comparison' set of dots and then a decision is made as to which of the arrays contained the most dots. An example of a trial from this task is shown in Figure 1.2.

The question of whether this task taps similar underlying mechanisms to those of the Non-symbolic comparison task (i.e. the ANS) was addressed by Gilmore and colleagues, who found evidence that performance on both types of tasks was significantly correlated in children aged between 5 and 11; More specifically, these authors found that performance on two types of Non-symbolic comparison tasks (one involving the comparison of smaller arrays of squares between 1-9, and the other involving comparison of larger arrays of squares between 5-22) showed medium-to-large, significant correlations with non-symbolic addition performance (Gilmore et al., 2014), supporting the proposal that performance on both tasks may rely on similar processes.

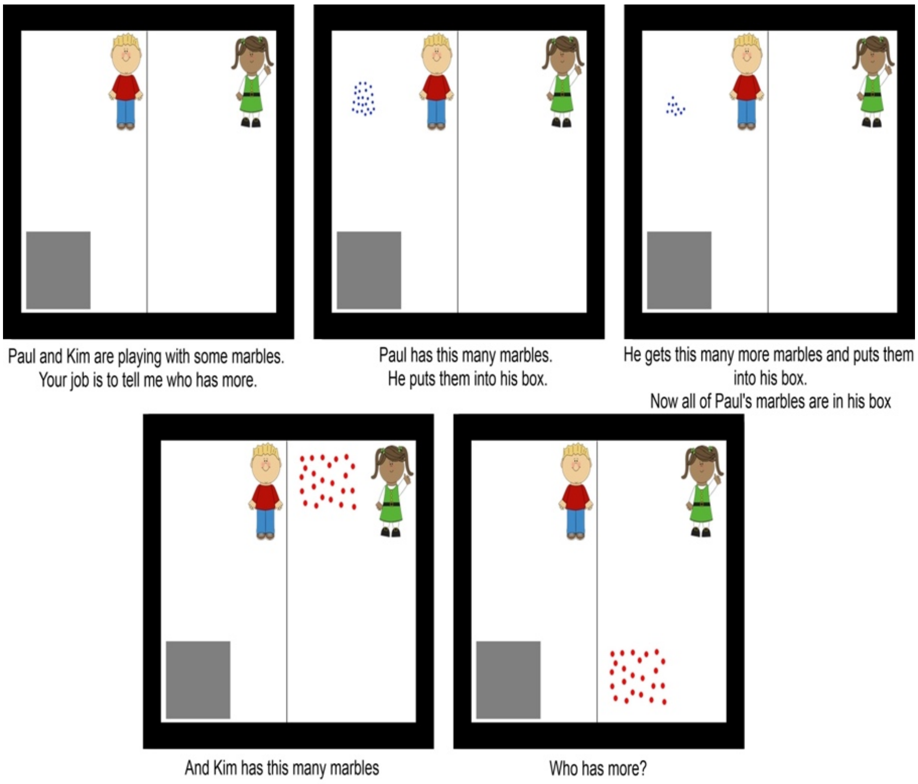

Figure 1.2. Example of a trial from the non-symbolic addition task

Several studies (Barth et al., 2008; Barth et al., 2005; Li et al., 2017) have found that young children can perform above chance on the Non-symbolic addition task and show the same pattern of responding as adults (characterized by significant ratio effects).Furthermore, performance on this task has also been found to be related to early maths abilities. Gilmore, McCarthy and Spelke (2010), found that those children (who had just begun primary school) who performed better on the task also tended to have a greater grasp of the maths curriculum, even after controlling for intelligence and literacy skills. This finding suggests that there is a link between approximate addition skills and early number acquisition that is not explained solely by academic aptitude. Wong et al. (2010) also found that performance on this task was significantly related to 6 –year-olds' arithmetic performance. Hyde, Khanum and Spelke (2014) trained 6-7-year-olds using Non-symbolic addition and found that this training led to significant improvement in arithmetic performance, compared to children who engaged in non-numerical comparison and addition tasks (involving line lengths and brightness), further supporting a link between task performance and numerical development.

However, it is possible that performance on this task may also rely on other skills, such as working memory and attentional control. In the task, children must attend to, and remember, the approximate quantity of the first comparison array. They then must approximately add the quantity of the first array to the second array, then hold the total in memory and compare it to the sum array. In dot comparison tasks, simultaneous presentation of the stimuli allows for a direct comparison of the numerosities. Therefore, it would be predicted that this task would be quite difficult for younger children. Indeed, Gilmore et al. (2010) found that 5 to 6-year-old children performed rather poorly on the task (between 62-66% overall accuracy), although they did perform significantly above chance. There may also be an inhibitory component to the task, as this task includes incongruent trials, in which either the magnitude of the sum or comparison arrays is negatively correlated with dot size, in a similar way to the Non-symbolic comparison task. However, given that the arrays are presented sequentially, perhaps this reduces the inhibitory demands of the task. Nonetheless, dot size still must be inhibited on incongruent trials, to arrive at the correct solution.

1.2.4 Symbolic magnitude

Number comparison tasks (see Figure 1.3) typically measure children's ability to compare two simultaneously-presented Arabic digits, based on their magnitude (e.g., Rousselle & Nöel, 2007; Vogel, Remark & Ansari, 2015). There is considerable support linking performance on these tasks with mathematical achievement (e.g., Castronovo & Göbel, 2012; Durand, Hulme, Larkin & Snowling, 2005; Budgen & Ansari, 2011; De Smedt, Verschaffel & Ghesquière, 2009; Kolkman, Kroesbergen & Leseman, 2013; Lonneman, Linkersdörfer, Hasselhorn & Lindberg, 2011; Mundy & Gilmore, 2009; Sasanguie, De Smedt, Defever & Reynvoet, 2012; Sasanguie, Göbel, Moll, Smets & Reynvoet, 2013; Sasanguie, Van den Bussche & Reynvoet, 2012; Vanbinst, Ghesquière & De Smedt, 2012; Vogel et al., 2015; Xenidou-Dervou et al., 2017), suggesting that Symbolic magnitude-processing skills play an important role in numerical development. De Smedt et al. (2013) found that more developmental studies found a relationship between Symbolic comparison and maths, compared to studies which measured Non-symbolic comparison, which highlights how numerical magnitude-processing skills may be more strongly involved in the development of maths skills, which perhaps is unsurprising given that much of maths learning involves the processing of Arabic numerals.

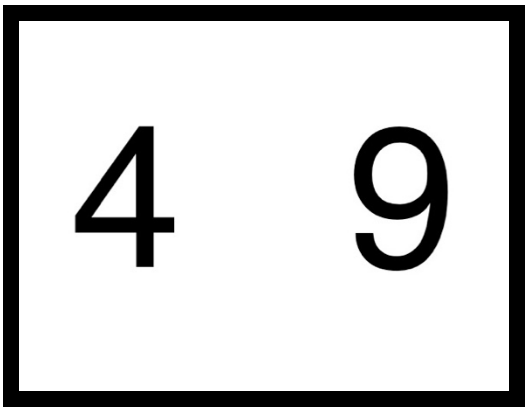

Figure 1.3. An example of a trial in the number comparison task

The results of meta-analytic studies are supportive of a link between symbolic magnitude-processing skills and maths achievement, and have found that this link is stronger than the relationship between non-symbolic magnitude-processing skills and maths achievement (Fazio et al., 2014; Schneider et al., 2016). These meta-analyses also suggest that symbolic magnitude-processing skills emerge in their importance to numerical development just after children have begun primary school (given that symbolic skills were found to be related to maths from around the age of 7 in these meta-analyses), at which time children are beginning to learn about the symbolic number system. Consistent with this proposal, Lyons et al. (2014) found that Number comparison performance was an important predictor of arithmetic amongst children aged between 7 and 12 (but see Attout et al., 2014; Sasanguie & Vos, 2018). These studies support the assertion that the importance to numerical development of Number comparison abilities may emerge after children have already began formal schooling, around the age of six.

However, it is important to note that the processing and representation of symbols not only depends upon an understanding of their magnitude, but also depends on an understanding of the order of the symbols within the number system. Therefore, it is plausible that performance on Symbolic comparison tasks may also depend on the extent to which children understand the relations between numbers, which the meta-analyses mentioned previously did not account for. Indeed, Lyons et al. (2014) found that performance on a Number ordering task (in which children had to judge whether three digits were in the correct canonical order) was correlated with Symbolic comparison performance across their sample. Furthermore, the authors found that whilst Symbolic comparison was the strongest predictor of maths amongst children aged between 7 and 9, Number ordering performance became as strong a predictor by age 9, after which time it became a stronger predictor than Symbolic comparison. Sasanguie and Vos (2018) found that Number ordering performance fully mediated the relationship between Symbolic comparison and maths amongst 6-7-year-old children. Furthermore, Attout et al. (2014) did not find that Symbolic magnitude-processing skills were correlated with arithmetic at any time-point in their longitudinal study; they did, however, find that both Number ordering and Symbolic comparison tasks correlated with each other at each time-point. Number ordering skills also concurrently correlated with calculation skills at age 6, and with complex calculation at age 7. These studies show that the processing of numerical information not only involves an understanding of the magnitude of the numbers within the number system, but also an understanding of the ordinal relationships between symbolic numbers.

In both Study 1 and 2, Symbolic comparison and ordering tasks were included, which allowed for a comparison of the predictive power of both to maths achievement, at both longitudinal and cross-sectional levels, and across development. Given the importance of Number ordering in mathematical development, as discussed earlier, it would be predicted that this measure would be as important to maths achievement as symbolic magnitude, although perhaps only for older children, by which stage it would be expected that numerical ordering skills would begin to overshadow symbolic magnitude in terms of its importance to mathematical development amongst older children. The correlations between performance on ordinal and magnitude tasks would also be analysed to investigate the extent to which order-processing skills are also involved in tasks which measure symbolic and non-symbolic magnitude.

Table 1.3. Table showing the results of three meta-analyses regarding the relationship between mathematical achievement, and both symbolic and non-symbolic magnitude

Study	Measure	12 or younger	17 or older
Chen & Li (2014)	Non-symbolic magnitude	.25	.22

Study	Measure	Younger than 6	6-18	Older than 18
Fazio et al. (2014)	Non-symbolic magnitude	.40	.17	.21

Study	Measure	Younger than 6	6-9	Older than 9
Schneider et al. (2016)	Non-symbolic magnitude	.31	.22	.26
	Symbolic magnitude	-	.28	.35

1.2.4.1 Is Symbolic or Non-symbolic magnitude a stronger predictor of maths?

There is some evidence from meta-analyses to suggest that non-symbolic magnitude is related to maths achievement (see Table 1.3), and the general consensus from these meta-analyses is that these skills are more strongly related to numerical development in studies involving younger children, which would support the involvement of the ANS in the development of early maths skills at the beginning of primary school (but see De Smedt et al., 2013). To test the directionality of the relationship between non-symbolic skills and maths achievement, Chen and Li (2014) analysed both prospective and retrospective longitudinal studies (which again they found to be underpowered) and found medium correlation coefficients of .24 and .17, respectively, from which they concluded that neither direction of the ANS and maths relationship could be rejected, which also shows that a conclusion is difficult to draw concerning whether the ANS leads to the development of numerical skills, or whether school experience leads to improvements in ANS acuity.

The results of two meta-analyses (Fazio et al., 2014; Schneider et al., 2016) have highlighted how symbolic magnitude-processing skills are stronger predictors of maths skills across development. Fazio et al. (2014) found that amongst a sample of 10-year-olds, symbolic and non-symbolic tasks loaded onto two separate factors that both independently influenced maths achievement. However, they found that the symbolic factor explained around 30%-45% more variance more in maths achievement than the non-symbolic factor. These results suggest that the ANS may play a minor role in mathematical development amongst older children, as symbolic magnitude-processing skills are now shown to be more important at this stage of development. Nonetheless, both symbolic and non-symbolic skills are seen to independently influence mathematical achievement, which supports the idea of separate and distinct systems for approximate and exact numerical abilities (e.g., Feigenson et al., 2004).

Schneider et al. (2016) showed that symbolic magnitude-processing skills were more strongly related to maths achievement than non-symbolic magnitude-processing skills amongst children aged six and older (the lack of studies included which assessed symbolic magnitude-processing skills in young children meant that no comparison could be drawn between both types of magnitude-processing skills and maths in the early years of schooling). However, De Smedt and colleagues (De Smedt, Noël, Gilmore

& Ansari, 2013) found in their review that for Non-symbolic comparison studies, most developmental studies did not find a significant relationship with maths, a finding which is in contrast with the meta-analyses. It should be noted, however, that two of these meta-analyses (Chen & Li, 2014; Schneider et al., 2016) included most non-significant developmental studies listed by De Smedt et al. (2013), although Fazio et al. (2014) only included two of these studies in their meta-analysis.

Furthermore, Chen and Li reported evidence of publication bias in their own meta-analysis (although no such evidence was found in the Schneider et al. meta-analysis), suggesting that these authors included more studies which found positive results regarding the relationship between non-symbolic magnitude-processing skills and maths achievement. These meta-analyses suggest that the ANS, as indexed by performance on non-symbolic magnitude tasks, may exert some influence over early numerical development, but that its importance gives way to the emergence of symbolic magnitude-processing skills amongst older children, presumably due to the increasing reliance of mathematical skills upon symbolic number knowledge as children develop.

Based on these results, it would be reasonable to hypothesize in the current study that non-symbolic magnitude-processing skills would play a more important role than symbolic magnitude skills in the early development of numerical abilities, at the beginning of primary school. It could be expected that the importance of symbolic magnitude skills would come to the fore at a later stage (possibly around the age of six), and these skills would remain important to mathematical abilities for older children.

1.2.4.2 What is the nature of the relationship between symbolic and non-symbolic magnitude?

At a neurological level, there is some evidence of an overlap in areas activated by both symbolic and non-symbolic magnitude-processing tasks (e.g. Sokolowski, Fias, Mousa & Ansari, 2017; Sokolowski, Fias, Ononye & Ansari, 2017; Holloway, Price & Ansari, 2010). At the behavioural level, several studies have shown that both Number and Non-symbolic comparison tasks elicit distance effects (e.g., Holloway & Ansari, 2008; Maloney et al., 2010; Sasanguie, De Smedt, Defever & Reynvoet, 2012; van Opstal & Verguts, 2010). However, some evidence suggests that these respective effects are unrelated, which suggests that the mechanisms responsible for processing symbolic and non-symbolic magnitude are also unrelated.

Sasanguie, De Smedt, Defever and Reynvoet (2012) assessed symbolic and non-symbolic comparison skills in children in Kindergarten, grade 1, grade 2 and grade 6. For both the symbolic and non-symbolic comparison tasks, the size of the distance effect was calculated using regression slopes, with increasing slope steepness reflecting greater distance effects. After controlling for grade, the slopes for both tasks were found to be uncorrelated. However, the strength of the symbolic distance effect was found to be moderately correlated with maths, whilst the non-symbolic distance effect was unrelated to maths achievement, after controlling for grade, suggesting that symbolic magnitude-processing skills are more closely related to maths achievement than non-symbolic skills in a wide age-range of children. Similarly, Holloway and Ansari (2008) did not find a relationship between symbolic and non-symbolic distance effects (using a composite measure based on reaction times) in comparison tasks, in a sample of six to eight-year-old children. However, only the symbolic distance effect predicted mathematical fluency. Even in an adult study, these distance effects have been found to be unrelated. Maloney et al. (2010) did not find a significant correlation between distance effects from both symbolic and non-symbolic comparison tasks across two experiments.

These results suggest that although both Symbolic and Non-symbolic magnitude tasks elicit similar effects, which are proposed to reflect the representation of magnitude along the mental number line, many studies have found that these effects are unrelated, both for adults and children. This calls into question the assumption that Symbolic and Non-symbolic magnitude are processed by the same system and, therefore, also calls into question the assumption that the ANS is the precursor to the acquisition of symbolic number knowledge.

To test whether a link exists between the mechanisms underlying the processing of both symbolic and non-symbolic magnitude, correlations between both types of tasks would be analysed in both studies. If performance on symbolic and non-symbolic magnitude tasks was found to be unrelated, both for young and older children, then this would be evidence in support of the prediction that the mechanisms responsible for the processing of these skills are unrelated, and therefore questions the assumed role of the ANS in early numerical development.

1.2.5 Number line estimation

The Number line task (see Figure 1.4) measures either individuals' ability to estimate the position of an Arabic symbol on a non-symbolic number line (number-to-position task), or their ability to estimate the Arabic digit which corresponds to a certain position on the number line (position-to number task), although this task can also involve fractions, decimals or even non-symbolic quantities.

Since many researchers argue that the number sequence is mentally represented along a mental number line (e.g., Bonato, Zorzi, & Umiltà, 2012; Kaufman, Vogel, Starke, Kremser, & Schocke, 2009; Link, Huber, Nuerk & Moeller, 2014; Moyer & Landauer, 1967), it could be argued that number line estimation tasks may tap these underlying representations of number along a mental number line. Accordingly, studies have investigated which type of function best fits children's patterns of estimations; the underlying assumption is that initially, young children's estimations of number along the number line show a logarithmic pattern (due to the imprecision of their mental number line in the early years), but become more linear with development (Berteletti, Lucangeli, Piazza, Dehaene & Zorzi, 2010; Siegler & Booth, 2004; Siegler & Opfer, 2003). This is consistent with the idea that the ANS is rather imprecise in generating representations of magnitude, due to the increasing overlap between numbers as the magnitude of numbers increase, with the assumption being that these representations gradually become more precise with age.

Figure 1.4. Example of a trial from the number line task

Performance on the Number line task has been found to be related to several mathematical measures, in studies of children even as young as three, suggesting that estimation skills may play a role in the development of early mathematical abilities (Berteletti, Lucangeli, Piazza, Dehaene & Zorzi, 2010; Booth and Siegler, 2008; Siegler & Booth, 2004; Siegler and Ramani, 2009). In a meta-analysis of the relationship between number line estimation and mathematical abilities, Schneider et al. (2018) found an overall medium-to-large effect size of .44 between Number line performance and maths achievement, whilst effect sizes increased with age (.30 for under 6's; .44 for 6-9-year old's and .49 for 9-14-year-olds), which suggests that estimation skills are involved in the development of mathematical skills across childhood. According to a recent review (Schneider, Thompson & Rittle-Johnston, 2017), the relationship between Number line estimation and maths achievement is stronger than the relationship observed between maths and Symbolic comparison amongst studies of children aged 6 and above (but similar for children younger than

6), an interesting finding given the evidence in support of the number comparison task as a predictor of maths ability (e.g., Fazio et al., 2014; Schneider et al., 2016). Therefore, it appears that estimation skills may be an important factor in mathematical development, which perhaps is not so surprising, given that the number line is an integral part of basic maths learning (National Council of Teachers of Mathematics, 2006).

Consequently, this measure was included in both experimental studies in this chapter. I used 1-10 and 1-20 scales with younger children and 0-100 and 0-1000 scales with the older children, and predicted that performance on this task would be found to be important to maths development across development, perhaps becoming even more important to numerical development for older children.

1.2.6 Summary of magnitude and estimation

The evidence in support of the role of non-symbolic magnitude in early numerical development is far from convincing. This is a concerning point, especially given the interest in maths interventions aimed at training the ANS (e.g. Park & Brannon, 2013, 2014; Van Herwegen, Costa & Passolunghi, 2017). Although the results of meta-analyses suggest that the ANS plays a role in mathematical development in the early years of schooling (e.g., Chen & Li, 2014; Fazio et al., 2014; Schneider et al., 2016), there are some major issues with how the ANS is measured, with respect to the Non-symbolic comparison task. These issues stem from the lack of a standardized version of the task, so there is considerable variation between studies in terms of which visual characteristics are controlled for, how performance is measured and how stimuli are presented in the task, which may contribute to why the reliability and validity of the dot comparison task has also been questioned (e.g., Inglis & Gilmore, 2013, 2014; Maloney et al., 2010; Price et al., 2012). A final issue concerns whether this task measured the ANS, or whether it also measures other skills such as Inhibition (Clayton & Gilmore, 2015; Clayton, Gilmore & Inglis, 2015; Gilmore et al., 2013; 2016). However, there is evidence in support of an alternative measure of the ANS; the Non-symbolic addition task, which has not only been found to be related to academic achievement in children (Gilmore et al., 2010; Wong et al., 2010), but has also been shown to be a useful intervention for improving children's maths skills (Hyde et al., 2014).

On the other hand, it has been relatively well established that Symbolic magnitude-processing skills play an important role in maths development, from around the age of 7, and has been found to be a stronger predictor of children's maths abilities than non-symbolic magnitude-processing skills (De Smedt et al., 2013; Fazio et al., 2014; Schneider et al., 2016). However, an important point is that these meta-analyses did not control for Numerical ordering abilities, even though ordinality is also an important property of numbers (Gallistel & Gelman, 1978), and that Number ordering abilities have also found to be a stronger predictor of maths abilities than Symbolic comparison, when the two measures have been used in the same study (e.g., Attout et al., 2014; Lyons et al., 2014).

Overall, it appears from the results of meta-analytic studies that Symbolic magnitude-processing skills are more strongly related to maths than Non-symbolic magnitude skills, and that the underlying mechanisms for the processing of these skills appears to be unrelated in studies of adults and children (e.g., Holloway & Ansari, 2008; Maloney et al., 2010; Sasanguie, De Smedt, Defever & Reynvoet, 2012). This casts doubt upon the supposed role of the ANS as the stepping stone between approximate and exact numerical skills, and the subsequent development of early mathematical skills.

Finally, the evidence supports the importance of Number line estimation skills in mathematical development; specifically, it appears that the strength of the relationship increases with age and may be even stronger than the relationship between Symbolic comparison and maths amongst children aged six and above (Schneider et al., 2018; Schneider, Thompson & Rittle-Johnston, 2017), which could be due to the process of automatization of the number system around this age.

In summary, it appears that there is much stronger evidence in favour of symbolic magnitude skills and estimation skills in the development of mathematical abilities, than for non-symbolic magnitude skills. It is still possible that both domain-specific and domain-general skills are involved in children's early numerical development. In the following section, I will review the literature regarding the role of domain-general predictors of mathematical development, such as executive functioning and working memory.

1.3 Domain-general precursors of mathematical development

1.3.1 Executive functions

Executive functions refer to processes that are involved in goal-directed behaviour and problem-solving; three of which are shifting, working memory updating and inhibition, which are separable, but also share some underlying commonality (Miyake et al., 2000). It has been proposed that the Central Executive (CE), which is involved in allocating working memory resources to tasks that are handled by the two slave systems, as well as controlling and monitoring cognitive processes (Baddeley, 2000), is also involved in the coordination of executive functioning processes (Miyake et al., 2000).

In the following subsections, I will discuss the literature that has investigated the extent to which each of these executive functions are related to maths to provide an insight into which higher order cognitive processes may be important to different aspects of mathematical development and performance.

Table 1.4. Table showing the results of four meta-analyses regarding the relationship between executive function processes and both maths and reading/literacy achievement

Friso-van den Bos et al. (2013) 4-12-year-olds	**Measure**	***r***	
	Inhibition & maths	.27	
	Shifting & maths	.28	
Allan et al. (2014)	**Measure (age)**	***r***	
	Inhibition & maths (3-5)	.29	
	Inhibition & maths (5-6)	.27	
	Inhibition & literacy (overall)	.25	
	Measure (age)	***r*** (Reading)	***r*** (Maths)
Jacob & Parkinson (2015)	Inhibition (3-5)	.27	.29
	Inhibition (6-11)	.36	.35
	Inhibition (12-18)	.33	.33
	Shifting (Overall)	.42	.34
	Measure (Age)	***r*** (Reading)	***r*** (Maths)
Yeniad et al. (2013)	Shifting (Younger than 6)	.20	.22
	Shifting (6-10)	.09	.23
	Shifting (Older than 10)	.32	.32

1.3.1.1 Inhibition

Inhibition refers to the process of overriding or withholding an automatic, dominant or pre-potent response (Miyake et al., 2000). According to Bull and Lee (2014), inhibition is involved in suppressing inappropriate mathematical strategies (e.g., selecting the appropriate operation in arithmetic, based on the sign between the operands) and is responsible for suppressing the retrieval of number bonds (e.g., automatically retrieving ‘8’ when shown the sum ‘4 + 2’).

Table 1.4 outlines the results of four meta-analyses on the relationship between executive functioning and both maths and reading achievement. The results suggest that inhibition does not play an important role in early numerical development, but may be more strongly involved in more mature maths performance (from around the age of six and onwards). Furthermore, the strength of the relationships between inhibition and both numeracy and literacy are similar, suggesting that inhibition skills may be somewhat involved in the development of both skills.

A measure of inhibition was included in Study 2, not only to assess whether it was related to maths achievement, but also to test the finding of Gilmore et al. (2013), that the relationship between Non-symbolic comparison and maths achievement disappears after controlling for inhibition skills. This would support the proposal that performance on the Non-symbolic comparison task involves other skills, and is not necessarily a pure measure of the ANS.

1.3.1.2 Shifting

Shifting refers to the ability to mentally switch between different situational aspects or tasks (Miyake et al., 2000), and may be involved in mathematical areas such as counting in different units (counting in both feet and centimetres when measuring height), or switching between different solution strategies (Clements, Samara & Germeroth, 2016), or switching between operations in calculation (Bull & Lee, 2014). Table 1.4 shows that shifting skills are somewhat related to maths achievement in children, with a stronger effect shown for older children (Yeniad et al., 2013), although

Friso-van den Bos et al. (2013) found in their meta-analysis that effect sizes were higher for studies with younger children. Shifting also appears to be somewhat linked to reading skills in younger and older children, although not for children aged 6-10, suggesting some link between shifting processes and numeracy and literacy skills.

1.3.2 Working Memory

Working memory is responsible for the temporary storage and processing of verbal and visual information whilst another task is being performed (Baddeley, 2000; Baddeley and Hitch, 1974). Baddeley and Hitch's model of working memory as consisting of four components; an attentional control system (Central Executive); two temporary stores (the Visuo-Spatial Sketchpad and the Phonological Loop), and an additional component (the Episodic buffer) which integrates information from the slave systems. Working Memory can be further subdivided into two main processes (Ecker, Lewandosky, Oberauer & Chee, 2010); Working Memory capacity (WMC), which reflects the amount of verbal or visual information that can be held by the temporary visual and verbal stores; and Working Memory updating (WMU), which consists of three subcomponents; retrieval (involving the retrieval of information from Working Memory); transformation (which involves the manipulation of information in Working Memory) and substitution (replacing old information held in Working Memory with new information). Ecker et al. (2010) used structural equation modelling to assess the links between WMU and WMC measures in adults, and found that WMC measures were predicted by the retrieval and transformation subcomponents of WMU. However, substitution did not predict WMC performance, suggesting that this component is unique to updating processes. The findings of Ecker and colleagues' study suggests that whilst there is some overlap between WMU and WMC processes, there is also a degree of separation between these constructs, so it is important to consider them as separate entities within the umbrella term of WM processes.

Table 1.5. Table showing the results of two meta-analyses regarding the relationship between WM processes and maths achievement

Friso-van den Bos et al. (2013)	**Measure**	***r***
4-12-year-olds	Visuo-spatial updating	.34
	Verbal updating	.38
	Visuo-spatial sketchpad	.34
	Phonological loop	.31
Peng et al. (2016)	**Measure**	***r***
Children and adults	Visuo-spatial working memory	.31
	Verbal working memory	.30

1.3.2.1 WM Updating (WMU)

WMU has been proposed to be involved in keeping track of what calculations have already been performed and mentally revising temporary information during mathematical performance (Bull & Lee, 2014; Clements, Samara & Germeroth, 2014; DeStefano & LeFevre, 2010). Furthermore, Cragg and Gilmore (2014) argue that working memory skills are likely to be important to two specific components of mathematics; the retrieval of mathematical facts from memory and to procedural knowledge (knowledge of how to carry out certain arithmetical procedures).

Indeed, there is evidence to suggest that WMU plays an important role in mathematics development across childhood. For example, Lan et al. (2011) found that performance on a Sentence completion task was a strong predictor of calculation skills in both Chinese and American pre-schoolers. In another paper (Kolkman, Hoijtink, Kroesbergen & Leseman, 2013), WM updating skills (measured by a Listening recall test) were found to be an important predictor of 5-year-old children's performance on Number line and Number comparison tasks, which themselves have been proposed as being important to the development of mathematical skills. Furthermore, fourth-grade children, who were identified as possessing good updating skills, were better at arithmetical word problems (but not on vocabulary), compared to children with lower updating skills (Passolunghi & Pazzaglia, 2004). As shown in Table 1.5, both verbal and visuo-spatial updating skills moderately predicted maths achievement amongst studies of 4-12-year-olds, with higher effect sizes found for studies of older children on visuo-spatial updating (Friso-van den Bos et al., 2013), suggesting that these skills may be somewhat related to maths across development, although the evidence discussed earlier suggests that WMU skills play a role in numerical development during the primary school years.

1.3.2.2 Visuo-spatial WM

The Visuo-spatial sketchpad (VSSP) is involved in the temporary storage and processing of both visual and spatial information in working memory (Rasmussen & Bisanz, 2005). It has been proposed that the VSSP acts as a mental whiteboard for children when solving mathematical problems, allowing them to mentally represent a problem and to manipulate the information mentally so that a correct solution can be found (e.g. Abrahamse, van Dijck, Majerus & Fias, 2013; Alloway & Passolunghi, 2011; Fias & van Dijck, 2016).

There is evidence to suggest that visuo-spatial skills play an important role in early numerical development (e.g., Passolunghi, Cargnetti & Pastore, 2014; Passolunghi & Costa, 2014; Soto-Calvo, Simmons, Willis & Adams, 2015; Szűcs, Devine, Soltèsz, Nobes & Gabriel, 2013; Van der Ven et al., 2013), which implies that children rely on visuo-spatial strategies for solving mathematical problems before they are able to use verbal strategies, such as sub-vocal rehearsal. This assertion is also supported by evidence which suggests that training using visuo-spatial games leads to improved numeracy skills in young children (Passolunghi & Costa, 2014; Van der Ven et al., 2013).

As children develop, however, it may be the case that they rely less on visuo-spatial strategies and more on verbal strategies for solving mathematical problem. For example, Rasmussen and Bisanz (2005) found that preschool children engaged in arithmetic using visuo-spatial skills, whilst children in grade 1 were more likely to rely on verbal skills. Furthermore, De Smedt et al. (2009) found that visuo-spatial WM (Block recall and Visual patterns) predicted maths amongst grade 1 children (but not when they were in grade 2), whilst the opposite pattern was observed for verbal WM (non-word repetition and digit span forwards). These studies propose that a shift occurs early in the primary school years, from the importance of visuo-spatial skills in mathematical problem-solving, to the importance of verbal strategies.

Yet another proposal suggests that older children utilize either visuo-spatial or verbal strategies depending on the type of mathematical problem they have to solve. For example, McKenzie, Bull and Gray (2003) suggests that older children use a mixture of visuo-spatial and verbal strategies in mathematics, suggesting that verbal strategies do not completely override visuo-spatial strategies previously utilized by children, but that the two strategies can co-exist and are activated under different conditions (but see Bull, Epsy & Wiebe, 2008; Meyer, Salimpoor, Wu, Geary & Menon, 2010).

Further discussion of a visuo-spatial WM task that involves order-processing skills (Backward matrices), which has been linked to maths achievement, is included in Chapter 2.

1.3.2.3 Verbal WM

The Phonological loop (which is tapped by verbal WM tasks) is comprised of a phonological store, which temporarily stores auditory information, and an articulatory loop, which is involved in the sub-vocal rehearsal of this auditory information (Baddeley, 2000). The role of verbal working memory in maths development may involve the sub-vocal rehearsal of operands during calculation, and in the rehearsal of the counting sequence as children move out of the strategy of finger-counting. DeStefano and LeFevre (2004) argue that verbal skills are involved in single-digit calculation when counting is used to solve problems, whilst its involvement in multi-digit calculations involves verbally maintaining the outcome of the calculations already performed.

As mentioned previously, verbal working memory skills may become important to maths later in development than visuo-spatial working memory skills. For example, De Smedt et al. (2009) found that it was only when children were aged 7 that verbal working memory predicted children's maths achievement, whilst Rasmussen and Bisanz (2005) found that the older children (aged between 6 and 7) solved arithmetical problems using a verbal strategy. Table 1.5 shows relationships of similar strength between visuo-spatial and verbal working memory, both in a meta-analysis involving children (Friso-van den Bos et al., 2013) and in one involving studies of both adults and children (Peng et al., 2016). Friso-van den Bos and colleagues found that there were higher effect sizes found for studies of younger children in regard to studies that measured visuo-spatial sketchpad, which supports the proposal mentioned earlier that visual-spatial skills exert a strong influence over early numerical development.

Further discussion of the Order working memory task (a verbal WM task involving the retention of serial order information), which has been found to be linked to maths achievement, is included in Chapter 2.

1.3.3 Summary of the role of domain-general predictors in mathematical development

The evidence from several meta-analyses (Allan et al., 2014; Friso-van den Bos et al., 2013; Jacob & Parkinson, 2015; Peng et al., 2016; Yeniad et al., 2013) indicates that there is evidence to support the role of both executive functioning and working memory processes in the development of numerical abilities. Regarding the link between executive functioning and maths achievement, both inhibition and shifting do not appear to be strongly related to maths achievement, suggesting that these skills are not important to early maths learning. In contrast, WMU and WMC measures were moderately related to maths, suggesting that perhaps they play a more important role in maths development, in comparison to Executive Functioning. The relationship between WMU measures and maths appeared to be relatively stable across development, with some evidence of stronger effects in older children (Friso-van den Bos et al., 2013). Visuo-spatial working showed stronger effects in samples with younger children, providing some support for the theory that these skills are important to the development of maths skills at the beginning of schooling; no age effect was found for verbal working memory (Friso-van den Bos et al., 2013). Nonetheless, these studies provide stronger support for the role of working memory in numerical development.

Table 1.6. Table outlining Domain-specific and Domain-general measures used in the experimental studies.

	Study 1 **(4-6-year old's)**	**Study 2** **(8-11-year-olds)**
Domain-specific measures	Number Ordering Number comparison Non-symbolic addition Number line Counting	Number Ordering Number comparison Non-symbolic comparison Number line
Domain-general measures	Order-Processing Questionnaire Order working memory Daily Events Choice reaction time	Order-Processing Questionnaire Order working memory Annual Events Visuo-spatial working memory Stop-signal Choice reaction time

1.4 Issues to be addressed in the thesis

The evidence does not appear to strongly suggest that domain-general or domain-specific skills alone are better predictors of mathematical achievement, and it is possible that both are involved in early number knowledge development. Consequently, both domain-specific and domain-general measures were included in the empirical chapters in this thesis (see Table 1.6).

An important point is that ordinality is also an important property of numbers, and whilst much research attention has focused on the importance of magnitude in numerical development, there is a relative dearth of research on the role of ordinality. Another related point is that, much like magnitude, ordinality is also both domain-specific and domain-general, as ordinality is also not restricted to the processing of the order of numerical information. Indeed, there is evidence to suggest that performance on verbal and visuo-spatial working memory tasks, which involve the processing of the correct order of novel sequences, have been shown to be involved in both typical and atypical maths development (e.g. Attout, Nöel & Majerus, 2014; Attout & Majerus, 2015; 2018; Morsanyi, van Bers, O'Connor & McCormack, 2018; Szűcs, Devine, Soltèsz, Nobes & Gabriel, 2013), which supports the proposal that order-processing skills may play an important role in numerical development, and thus warrants more research attention. A detailed review of the role of order-processing skills in maths development is included in Chapter 2.

In the following subsections, I will outline the general issues that I wish to address throughout this thesis, with reference to magnitude-processing and other domain-general factors.

1.4.1 What role does the ANS play in early numerical development?

As mentioned previously, several studies have found that performance on symbolic and non-symbolic comparison tasks elicit similar distance effects, although these appear to be unrelated (e.g., Holloway & Ansari, 2008; Maloney et al., 2010; Morsanyi, van Bers, O'Connor & McCormack, 2018; Sasanguie, De Smedt, Defever & Reynvoet, 2012). If the ANS is involved in the acquisition of symbolic number knowledge, and subsequently the early development of numerical abilities, then it would be reasonable to expect that performance on both symbolic and non-symbolic magnitude tasks would be related. However, this assertion appears to be without much research support, suggesting that the ANS may have nothing to do with the development of early mathematical skills. Whilst several meta-analyses (e.g. Chen & Li, 2014; Fazio et al., 2014; Schneider et al., 2016) have highlighted that non-symbolic magnitude skills are linked to early numerical development, nonetheless a firm conclusion regarding the direction of the relationship between the ANS and maths achievement cannot be reached.

Based on this evidence, I predict that symbolic and non-symbolic magnitude skills will be unrelated during the early years, although with experience of formal maths learning, I would predict that they would correlate for older children. This result would provide evidence that the underlying mechanisms responsible for the processing of symbolic and non-symbolic magnitude would have nothing to do with each other in the early years, further supporting the argument that the ANS is not necessarily the precursor to the development of maths skills in young children.

I also predicted that non-symbolic magnitude-processing skills would be unrelated to mathematical achievement at the end of children's first year of primary school, but would be found to play a role in numerical development over 1 year later, and amongst older children. This finding would support the assertion that the ANS may not be as important to early numerical development as previously thought, and that the reason for its emergence afterwards would be due to children's experience with formal maths learning, which would help to answer the question posed by Chen and Li (2014) regarding the directionality of the relationship between the ANS and mathematical achievement.

1.4.2 What role do domain-general factors (such as intelligence and socioeconomic status) play in numerical development across childhood?

There is some support for a link between socioeconomic status and maths skills (e.g. Davis-Kean, 2005; Morsanyi, van Bers, McCormack & McGourty, 2018; Schiller, Khmelkov, & Wang, 2002; Sirin, 2005; van Ewijck & Sleegers, 2010; Yang, 2003; von Stumm & Plomin, 2015), in that children from a lower socioeconomic background tend to perform worse in mathematics compared to children from a higher socioeconomic background. In a meta-analysis conducted by Sirin (2005), the link between mathematical achievement and socioeconomic status seemed to increase with age, between the ages of 5 and 18, which suggests that children's home background still may have an effect on their mathematical potential, and that this becomes more evident with development. However, this meta-analysis was conducted in the USA, and may be unrepresentative of the UK. However, Morsanyi and colleagues (Morsanyi, van Bers, McCormack & McGourty, 2018) found that amongst a sample of 8-11-year-olds, children with low maths ability tended to come from a lower socioeconomic background than children with high or average maths ability, which suggests that this effect is apparent amongst older children in primary school.

There is evidence to suggest that intelligence is linked to academic achievement, and to other socioeconomic outcomes, such as future income and future employment (Deary, Strand, Smith & Fernandes, 2007; Roth et al., 2015; Strenze, 2007). Amongst older children, Deary et al. (2007) found that intelligence measured at age 11 strongly predicted success in GCSE maths at age 16. Furthermore, Strenze (2007) found that intelligence at age 3-10 was predictive of academic success, future income and future occupation. This suggests not only that the underlying skills which tap into intelligence are important to mathematical achievement during the school years, but also may predict future employment and financial outcomes, which implies that those children who do not possess adequate intellectual skills may also struggle academically, which may have a large bearing on their future outcomes.

Given the evidence, I predicted that intelligence measures would be strongly related to mathematical development, both in older and younger children, given that these skills are intertwined with academic success. Regarding socioeconomic status, I also predicted that this measure would be strongly related to maths across development, given the meta-analytic evidence that supports the increasing influence of socioeconomic status on maths development with age. However, it is possible that a different pattern of results may be obtained, given that the Sirin (2005) meta-analysis was conducted in the USA. Nonetheless, the findings regarding the link between socioeconomic status and maths would be useful in examining the link between the two, in a sample of children from Northern Ireland, including both young and older children.

1.5 Summary and outline of the thesis

The literature reviewed in this chapter suggests that there are several factors which may differentially play a role in the development of maths skills. To this end, the overarching aim of this thesis is to investigate the role of ordinality in the acquisition of formal maths skills, particularly the role of non-numerical ordering.

There is now evidence which suggests that both numerical and non-numerical ordering skills are important predictors of typical maths development in young children at the beginning of primary school (e.g., Attout et al. 2014; Lyons & Ansari, 2015; Lyons et al., 2014; Sasanguie & Vos, 2018; Vogel et al., 2017) and ordering skills appear to be deficient amongst older children with Developmental Dyscalculia (e.g., Attout & Majerus, 2015; Morsanyi, Devine, Nobes & Szűcs, 2013; Morsanyi, van Bers, O'Connor & McCormack, 2018; Rubinstein & Sury, 2011). Chapter 2 includes a review of the literature regarding the link between ordering skills and maths. This thesis not only considered the role of numerical and non-numerical tasks which have been used previously in these studies, but also included two additional order-processing measures that have never been used before in the domain of mathematical cognition, to provide a more in-depth analysis of the relative contribution of numerical and non-numerical ordering abilities to the development of mathematical skills across childhood.

Chapter 2 will also focus on the motivation behind including the ordering for familiar tasks and familiar events measures, and the question of which types of ordering skills are important to maths achievement at different developmental stages. This chapter will conclude with an outline of the issues to be addressed, specifically concerning the role of order-processing skills in numerical development across primary school. These issues include;

- Assessing whether ordering skills are important to maths learning in primary school-age children and, if so, is this relationship restricted to the importance of numerical ordering, or are non-numerical ordering skills also important.
- Comparing the importance of ordinal, magnitude and estimation skills in maths development throughout primary school.
- Investigating the pattern of correlations between ordinal and magnitude tasks

Chapter 3 outlines a longitudinal study involving ninety children, who were tested (T1) in their first year of primary school (87 of which were followed up over 1 year later at T2) on magnitude, ordinal and measures of mathematical achievement. As well as trying to address the issues from Chapter 2, in relation to young children's maths learning, this chapter focused on investigating a number of specific issues;

- Investigating which skills are important to early numerical development in children who have just began primary school
- Assessing the strength of the correlations between T1 and T2 of ordinal and magnitude tasks, to investigate the stability of these predictors in the early years

Chapter 4 outlines a study involving one-hundred children in Key Stage 2 (aged between 8 and 11 years). In this study, ordinal and magnitude tasks similar to those in Chapter 3 were used. This study also investigated the role of other domain-general factors, such as inhibition and visuo-spatial working memory, in later maths development. This chapter also focused on investigating a number of specific issues;

- Investigating which skills are important to early numerical development in children who are approaching the end of primary school
- Assessing whether order-processing skills are also important to reading skills in older children

Chapter 5 includes a summary of the main highlights of the empirical studies. The implications of these findings will also be discussed, in terms of the theoretical and practical implications of the findings; how the predictors appeared to develop with age in terms of their relationship with maths achievement; a discussion of which results were unexpected and which findings were novel. A critique of the methods used in the thesis will then be presented, as well as suggestions for future research on the topic of ordering skills in maths development.

Chapter 2: The role of Ordinality in the development of early maths skills

2.0 Introduction

Ordinal knowledge reflects an understanding of the position in which a particular item lies within a sequence; these items can be numerical (such as the order of the Arabic numerals) or non-numerical (for example, the order of the letters of the alphabet, days of the week, months of the year, seasons of the year). If a child was asked to recite any of these numerical or non-numerical sequences, they would rely on the retrieval of these familiar, learned sequences from long-term memory, some of which are not mastered until later in childhood (Friedman, 2000a; 2000b). Nevertheless, there is also evidence to suggest that the order of temporal sequences (such as the sequence of familiar daily events) can be recited successfully even by young children (Friedman, 1977). Order-processing skills can also be measured by tasks in which individuals have to temporarily store, and then retrieve, the order of arbitrary, novel sequences, such as the order of a list of animal names (e.g. Order WM task; Majerus et al., 2006), suggesting that order-processing skills involve the retrieval of both familiar and novel sequences; the former from long-term memory, and the latter from short-term memory. Furthermore, Ordinality is seen to be innate, and not unique to humans, as there is evidence that sensitivity to ordinal relationships is evident in non-human species (Berdyyeva & Olson, 2010; Brannon, 2002; Brannon, Cantlon & Terrace, 2006; Brannon & Terrace, 1998; Cantlon & Brannon, 2006; Kessner & Holbrook, 1987; Ninokura, Mushiake & Tanji, 2003;

Petrazzini, Lucon-Xiccato, Agrillo & Bisazza, 2015; Terrace, Son & Brannon, 2003; Wang, Uhrig, Jarraya & Dehaene, 2015); whilst there is also evidence of infant's sensitivity to ordinality (Cassia, Picozzi, Girelli & de Hevia, 2012; de Hevia et al., 2017; Picozzi, de Hevia, Girelli & Cassia, 2010; Suanda, Tompson & Brannon, 2008), suggesting that ordinality has some evolutionary basis.

Ordinality is also an important property of numbers, much like magnitude, and the acquisition of ordinal knowledge is also an important milestone in learning to count (Gelman & Gallistel, 1978). In relation to the number system, ordinal information conveys the relative position that a number lies within the number sequence, and so gives a sense of the relationships between each number (Lyons & Beilock, 2011). The importance of ordinality to maths development can be seen in simple arithmetic. For example, subtraction relies on one operand being subtracted from the other in the correct order, as reversal of the operands will lead to an incorrect answer (e.g., 3 – 1 will give a different answer from 1 – 3). An understanding of ordinality is also important for the correct solving of more advanced arithmetical problems (with operations involving brackets), which follow the BODMAS rule; Brackets of (order), division, multiplication, addition and subtraction (Peng, Yen & Chen, 2012). Therefore, it may be the case that ordinal knowledge about the number system may also be an important contributor to the development of mathematical skills, although this topic has been relatively understudied in comparison to the role of magnitude. Furthermore, it is difficult to envisage how children can develop an intuitive grasp of the symbolic number system if they fail to understand the ordinal relationships between numbers, beyond simply rote-learning the number system (Lyons & Beilock, 2011), and Nieder (2009) argues that as our symbolic number knowledge develops, we become less reliant upon the representation of the actual quantity that each symbol conveys and begin to adopt a more ordinal representation of numerical symbols, which underlies the development of our mathematical competence from childhood to adulthood.

This shift from a reliance upon magnitude, to the emergence of ordinal knowledge of the number system, is consistent with the proposal, mentioned in the previous chapter, that knowledge about the magnitude of numbers emerges earlier than knowledge about the order of the number system (e.g. Colomé & Nöel, 2012; Wiese, 2007). Coupled with the assumption that the ANS plays a pivotal role in children's learning of the symbolic number system, and is subsequently thought to be strongly involved in early mathematical development (e.g. Chen & Li, 2014; Fazio et al., 2014; Schneider et al., 2016), these points highlight the assumption that magnitude plays a more important role in children's early maths learning, whilst ordinality may emerge as an important factor later in development. However, it should also be noted that children's learning of the counting sequence occurs prior to their understanding of magnitude (Sarnecka & Carey, 2008), suggesting that even young children can recite the count list before they fully understand the cardinal principle.

As mentioned earlier, ordinality is not only restricted to numbers. However, there is a relative paucity of research on the role of non-numerical ordering skills in numerical development amongst children, which the current thesis aimed to address. As mentioned in the previous chapter, Dehaene (1997) proposes that numbers are represented spatially along a mental number line. In line with this argument, some researchers argue that that there is a domain-general representational format which is involved in the representation and processing of ordered information in long-term memory, based on the representation of a mental number line (e.g. Arend, Ashkenazi, Yuen, Ofir & Henik, 2017; Bonato, Zorzi, & Umiltà, 2012; Cheung & Lourenco, 2015; Crollen & Nöel, 2015; Crollen, Vanderclausen, Allaire, Pollaris & Nöel, 2016; Dehaene, Bossini & Giraux, 1993; Franklin & Jonides, 2009; Lonneman, Linkersdörfer, Nagler, Hasselhorn & Lindberg, 2013; Moyer & Landauer, 1967; Seno, Taya, Ito & Sunaga, 2011), suggesting that both numerical and non-numerical information is represented spatially along a continuum, from left-to-right (in Western cultures).

Whilst other studies have found links between other non-numerical ordering measures and maths abilities in adults (Morsanyi, O'Mahony & McCormack, 2017; Vos, Sasanguie, Gevers & Reynvoet, 2017), the Attout et al. (2014) study was one of the first to show the importance of early non-numerical ordering skills to arithmetic amongst a sample of young children, as these authors found that performance on a verbal WM task (Order WM) was concurrently and longitudinally related to arithmetic performance in children who were tested between the ages of 5-8. One of the aims of the thesis was to build on the results of Attout et al. and to investigate whether order-processing skills are more important to numerical development amongst young children at the beginning of primary school (who were tested between the ages of 4-6) than magnitude skills. In particular, I was interested in the role of non-numerical order-processing skills, given the research support for these skills in mathematical development. As well as using similar measures to that of Attout et al. in Study 1, I also included other non-numerical order-processing measures that have not been used before in mathematical cognition research (see sections 2.2.3 and 2.2.4), to assess their relative contribution to the early development of mathematical skills.

Although many studies have focused on investigating which skills are important to the development of numerical skills during the early years of primary school (e.g. Attout et al., 2014; Sasanguie & Vos, 2018), some studies (e.g. Attout & Majerus, 2018; Lyons et al., 2014), have assessed order-processing skills in older children, but not with children who are preparing to leave primary school. Although Lyons et al. did assess children from grades 1-6, these authors did not include measures of non-numerical ordering skills, so their conclusions concerning the importance of ordering skills across childhood were based solely on children's performance on a Numerical ordering task. The aim of Study 2 was to investigate which skills are important to mathematical development amongst children aged 8-11 (Key Stage 2), who are preparing to finish primary school. This would also allow for an examination of the developmental trends concerning the correlations between each measure and maths achievement, to see whether certain skills become less or more important to maths learning for older children. Since many studies have found evidence that numerical ordering skills do not emerge as an important factor in numerical development until children are older (e.g. Attout et al., 2014; Lyons et al., 2014; Sasanguie & Vos, 2018), I would expect that numerical ordering skills would be more important to maths achievement amongst older children, than they might be for younger children. Furthermore, Study 2 also investigated whether the importance of order-processing skills is restricted to numerical development, or whether they also are related to the development of reading skills, particularly given that performance on the Order WM task has been linked to children's vocabulary development (Leclerq & Majerus, 2010; Majerus et al., 2006, 2009); novel word-learning ability (Majerus & Boukebza, 2013); and reading acquisition (Martinez Perez, Majerus & Poncelet, 2012), as the Order WM was originally developed as a measure within the domain of vocabulary development. Nonetheless, those studies mentioned previously did not include measures of order-processing skills for familiar content, such as processing order for familiar sequences of everyday tasks, or processing order for familiar sequences of daily events. In the thesis, the importance of these skills was assessed in both studies to investigate their relative contribution to numerical development across childhood, as these types of ordering skills have not been assessed in the domain of numerical cognition.

Another aim of the thesis was to assess the relationships between ordinal measures, and between both ordinal and magnitude measures (the issue of the relationship between symbolic and non-symbolic magnitude measures is dealt with in the previous chapter). Concerning the relationships between ordinal measures, if these measures are tapping a similar underlying construct, then significant correlations would be observed between all of these tasks. Indeed, evidence from neuroscientific studies (e.g. Fias, Lammertyn, Caessens & Orban, 2007; Fulbright et al., 2003; Ischebeck et al., 2008) suggests that performance on both numerical and non-numerical order-processing may involve the activation of similar brain areas (for a discussion, see section 2.2.2), suggesting that there may be a link, at the neurological level, between the processing of both numerical and non-numerical order. The current thesis aims to investigate whether, at the behavioural level, younger and older children's performance on numerical and non-numerical ordering tasks are also related.

Finally, if magnitude and ordinal measures are correlated, this would suggest that the underlying mechanisms responsible for the processing of magnitude and ordinality may be linked. Indeed, some authors argue that performance on Number ordering tasks may involve comparison processes. On Number ordering tasks, the reverse distance effect (whereby accuracy is lower and reaction times are quicker, as the numerical distance between the first and third numbers in a triad approaches 1) commonly observed for canonical-order trials is argued to reflect the importance of ordinality in the mastery of the number system (Lyons & Beilock, 2015). On the other hand, the distance effect commonly found for mixed-order trials may reflect the use of a comparison strategy (Sasanguie & Vos, 2018), as children compare each digit to its successor in order to arrive at the correct solution. This would suggest a link between numerical processing mechanisms involved during comparison and ordering performance, so it could be expected that performance on these tasks should be correlated for both younger and older children (but see Goffin & Ansari, 2016; Vogel et al., 2015).

The purpose of this chapter is to review the current evidence which supports the role of both numerical and non-numerical ordering abilities to numerical development. I will also discuss some of the limitations of the current literature, and propose some issues about the role of ordinality that I wish to address in this thesis. In Section 2.1, I will outline the evidence in support of the role of numerical ordering abilities in mathematical achievement, in developmental studies. In section 2.2, I will introduce the topic of non-numerical ordering skills. In particular, I will discuss how non-numerical skills are represented in the brain; how non-numerical order-processing skills have been linked to the deficits exhibited by individuals with Developmental Dyscalculia, as well as reviewing the literature behind two new types of ordering task that were used in both experimental studies (Order-Processing Questionnaire and Daily/Annual events task). This section will also involve discussion of the literature concerning two non-numerical order-processing measures that have been previously used in the literature (Order WM and Backward Matrices tasks). In section 2.3, I will discuss the limitations of the current literature on order-processing, and how the current study aims to improve on these limitations. Finally, section 2.4 outlines the specific issues regarding the role of ordinality in numerical development, and how each of these will be addressed in this thesis.

2.1 The role of numerical ordering skills in mathematical achievement in developmental studies

Numerical order-processing skills have typically been assessed using tasks that involve the judgement of whether dyads or triads of numbers are in the correct canonical order (see Figure 2.1), or whether they are either in ascending or descending order (e.g. Attout & Majerus, 2015; Attout, Nöel & Majerus, 2014; Lyons & Beilock, 2011; Lyons et al. 2014; Lyons & Ansari, 2015). These tasks have been used to assess whether the ability to process the order of numbers is related to maths achievement. In the following, I will review the evidence from developmental studies regarding the extent to which numerical ordering skills have been linked to mathematical achievement.

Figure 2.1. Example of a canonical order trial (with a numerical distance of 2) in the Number ordering task used in Study 1 (at T2) and Study 2. At T1, the task involved ordering cards numbered from 1-9 in forwards and backwards order

There is evidence that children's ability to process numerical order is related to maths achievement (Attout & Majerus, 2018; Attout et al. 2014; Lyons & Ansari, 2015; Lyons et al., 2014; Sasanguie & Vos, 2018, but see Vogel et al., 2015), suggesting that these skills may play an important role in the development of numerical abilities. Attout et al. (2014) measured children's ability to process numerical order using dyads, in which they had to indicate whether the numbers were in the correct canonical order, from left-to-right (half of the trials were in the correct canonical order, the other half were in the incorrect order). The authors found that performance on this task was concurrently related to arithmetic between the ages of six and seven, and concurrently related to complex calculation between the ages of seven and eight. Attout and Majerus (2018) extended these findings to a sample of 7-9-year-olds by showing that performance on the same Number ordering task explained variance in arithmetic scores, independent of Number comparison performance. The work of Attout and colleagues suggests that numerical ordering skills may not emerge in their importance to maths development until children are at least six years old, by which time in Belgium, these children are in their first year of primary school (which makes these children almost two years older than children in their first year of school in Northern Ireland).

These findings are supported by those of Lyons et al. (2014), who investigated the role of a wide range of basic numerical and non-numerical skills in the development of math in a large sample of children across grades 1-6 (ranging from 6-12 years old). Children's ability to process numerical order was measured using the ordinal judgement task, in which children were shown a triad of numbers and had to indicate whether the numbers were in the correct order, from left-to-right. Children in the first grade (aged 6-7-years-old) only saw triads with single-digit numbers, whilst children in the other grades saw both single and double-digit triads. Lyons and colleagues found that numerical ordering ability was not a strong predictor of children's arithmetic skills in grades 1 and 2; at this stage, both Number comparison and Number line performance were better predictors of arithmetic. However, Number order performance gradually increased in its predictive power. From grade 3 onwards (between the ages of 8 and 9 years old), Number ordering was a significant predictor of arithmetic and by grade six (children aged between 11-12 years old), it was the strongest of all of the other predictors. Furthermore, Lyons and Ansari (2015) found that it was performance on sequential canonical order trials (e.g. 1-2-3), in the Number order task, which explained the most unique variance in children's arithmetic scores (even after controlling for counting ability), which suggests that numerical ordering abilities, and particularly performance on these trials, may be considered to be an important building block for mathematical learning. These authors found that Counting skills were unrelated to performance on these trials, which suggested that this result was not due to children's over-familiarisation and over-learning of these sequential number triads. Together, these results suggest that numerical ordering skills are important to the development of numerical abilities in children from the age of six and above, and that they continue to be important until children are close to leaving primary school.

Sasanguie and Vos (2018) investigated the issue of whether numerical magnitude or numerical ordinal skills emerge first as important skills in early numerical development amongst first and second grade children, as it has been proposed that magnitude-processing skills emerge before ordinal skills (e.g. Colomé & Nöel, 2012; Michie, 1985; Wiese, 2007). Sasanguie and Vos found evidence that supported this proposal, as

Number comparison performance was shown to be important to arithmetic skills in first grade, whilst Number ordering skills (measured by a task involving judging the order of number dyads) were important to second grader's arithmetic skills, suggesting that there were differences in strategy use between the two age groups in terms of how they solved arithmetic problems.

Together, the findings from these developmental studies have consistently shown that numerical order-processing skills are related to numerical development in studies of children, although it must be noted that these studies have shown that numerical ordering skills are important from the age of six and onwards, who have had some experience of formal schooling. However, as mentioned in the previous chapter, one potential issue in interpreting these results is that they have not tested very young children, so it could be the case that chronological age may be an extraneous factor which may influence which particular skills are important at each stage of development. Another related point concerns whether there are also cultural variations in terms of the level of maths teaching that parents engage in with their children in the home environment. In Northern Ireland, children begin school on the first September after their 4th birthday, which makes them one of the youngest school-age children in the world (Eurydice at NFER, 2013), and although some of these studies have shown evidence of a link between numerical ordering abilities in children at the beginning of primary school, it is difficult to ascertain the extent to which this is due to any one, or more, of these differences, thus this makes it difficult to accurately compare the results of different studies across different countries.

There are also differences between studies regarding the version of the Number ordering task they have used. Some authors have used a version of the task involving dyads of numbers, involving only single-digit numbers (e.g. Attout & Majerus, 2018; Attout et al., 2014; Sasanguie & Vos, 2018; Vogel et al., 2015), whilst others have used triads, including double-digit numbers (e.g. Lyons & Ansari, 2015; Lyons et al., 2014). This may be one of the reasons why the authors who used number triads (Lyons & Ansari, 2015; Lyons et al., 2014) did not find that numerical ordering abilities explained variance in arithmetic scores for children in grades 1 and 2 (even though grade 1 children only saw single digits). Furthermore, as shown in Table 2 of Lyons et al. (2014), Number ordering appeared to be one of the most difficult tasks for younger children to perform, which may partly explain the lack of a significant predictive relationship between task performance and arithmetic in grades 1 and 2.

Another point of interest is that recent evidence has suggested that non-numerical ordering abilities may play a more important role in numerical development than numerical ordering skills (e.g. Attout et al., 2014), and also may explain more variance in adult's maths achievement than numerical ordering skills (e.g. Vos, Sasanguie, Gevers & Reynvoet, 2017). However, there is a lack of research into how these skills are involved in numerical development amongst children, and those that have investigated the role of non-numerical ordering skills have done so by only using certain non-numerical tasks. In the following subsection, I will review the evidence which suggests that non-numerical ordering skills may be involved in both typical and atypical numerical development, in order to provide a rationale for investigating their importance in typical mathematical development across childhood.

2.2 The role of non-numerical order-processing skills in mathematical achievement

Studies of non-numerical ordering ability have included Letter-order judgement (e.g. Lyons & Beilock, 2011; Sasanguie et al., 2017); Month-order judgement (e.g. Morsanyi, O'Mahony & McCormack, 2017) and tasks involving the judgement of whether horizontal lines of different lengths are in the correct canonical order (Attout & Majerus, 2015). Letter and Month order tasks involve the retrieval of familiar ordered sequences from long-term memory. However, the mathematical cognition literature has not assessed the role of temporal ordering skills (e.g. Friedman, 1977), which also involve the retrieval of familiar sequences from long-term memory, in studies of numerical development. The evidence supporting the role of these skills will be discussed in sections 2.2.3 and 2.2.4. Recent evidence has also investigated the role in numerical development of working memory skills, involving tasks which tap Visuo-Spatial WM (e.g. Mammarella et al., 2015) and Verbal WM (e.g. Attout et al., 2014), as these measures involve the retention and retrieval of novel, non-numerical ordinal information from short-term memory.

In the following subsections, I will review the evidence concerning the role of non-numerical ordering skills in explaining the deficits associated with Developmental Dyscalculia; I will review studies which have compared the patterns of activation during the processing of numerical and non-numerical order in the brain; finally, I will review the evidence concerning the non-numerical order-processing tasks used in the experimental studies.

2.2.1 Order-processing deficits in Developmental Dyscalculia

Developmental Dyscalculia (DD) is a specific impairment of mathematical ability which may affect 3.5–6.5% of the population (e.g., Butterworth, 2005; Kaufmann & von Aster, 2012; Morsanyi, van Bers, McCormack, & McGourty, 2018; von Aster & Shalev, 2007). Individuals with DD are characterized by moderate to extreme difficulties in fluent numerical computations in the absence of sensory difficulties, low IQ, or educational deprivation. It has been proposed by some authors that the core deficit in DD reflects a problem with processing magnitude (e.g. Dehaene, 1997; Mejias, Grégoire & Nöel, 2012; Skagerlund & Träff, 2014), although this view has been challenged by others (e.g., Iuculano, Tang, Hall and Butterworth, 2009; McCaskey, von Aster, O'Gorman Tuura & Kucian, 2015; Piazza et al., 2010). An alternative proposal regarding the core deficits in DD suggests that atypical ordering skills may be a core feature of the disorder, and therefore may be considered an important skill in the development of normal mathematical abilities. In a study in which both typical adults and adults with DD made judgments about symbolic and non-symbolic stimuli, Rubinstein and Sury (2011) found that adults with DD showed a ratio effect in a non-symbolic ordering task (where they were presented with 3 arrays of dots and had to judge whether the arrays were correctly ordered, regardless of whether the order was ascending or descending), which suggests that they do not have an ANS-related deficit. However, the authors found that adults with DD were impaired when making judgments about ordinality in the symbolic task (when they had to judge whether 3 numbers were in the correct canonical order). The authors reasoned that DD is characterized by a deficit in the ability to process order, rather than a deficit in the ability to process magnitude, providing further support for the idea that ordinality plays an important role in the development of math skills. Furthermore, Attout and Majerus (2015) found evidence of deficits in Number Order task performance amongst a sample of 8-12-year-olds with DD, compared to a control group who were matched on age, IQ and reading skills, supporting the hypothesis that numerical ordering abilities are affected in DD, amongst children who are preparing to leave primary school.

However, there is recent evidence to suggest that non-numerical order-processing skills may also be deficient in DD amongst older children (Attout & Majerus, 2015; Morsanyi, Devine, Nobes & Szűcs, 2013; Morsanyi, van Bers, O'Connor & McCormack, 2018), suggesting that the deficits in order-processing skills exhibited by individuals with DD are not necessarily restricted to problems with the ordering of numerical symbols. For example, Morsanyi, Devine, Nobes and Szűcs (2013) investigated the link between math and logic in children with Dyscalculia, high mathematics achievers and controls, in which they were given verbal transitive inference problems. These problems require the ordering of items according to certain properties (e.g. if Paul is taller than Sue, and Chris is taller than Paul, then one could reason that Chris is taller than Sue), which is similar to mental manipulations of numerical components within equations in maths. Although transitive problems are devoid of mathematical content, they share with maths the requirement that in order to come to a correct solution, effective order processing skills are necessary. For example, in the transitive inference mentioned above, a correct solution can be achieved by placing Paul, Sue and Chris into a hierarchical order based on their height. Similarly, in maths, correctly answering the problem $2 + 2 \times 5$ requires the knowledge that the 2×5 must be performed first, then 2 is added to the sum to achieve the correct answer of 12. The results showed that children with DD performed significantly worse than children with average or high maths skills, suggesting that children with DD are deficient in their ability to process order in these verbal problems, relative to their peers.

Attout and Majerus (2015) investigated the role of working memory (WM) for serial order in children with DD and a sample of typically developing children, who were matched on age, IQ and reading abilities. The children were given an item WM task (where they heard a monosyllabic non-word and had to repeat the word) and an Order WM task (where they heard lists of animal names and had to re-create the correct order of animals in the list that they heard), as well as a calculation task (1-minute pencil and paper test involving additions, subtractions and multiplications); symbolic and non-symbolic ordinal judgment tasks (judging whether two sets of lines or numerals were in the correct ascending order numerically) and symbolic and non-symbolic magnitude judgment tasks (judging which of two sets of lines or numerals were the most numerous). The authors found evidence of deficits in order WM abilities and ordinal judgment abilities in the DD group, compared to the typically developing children. These deficits may impact upon DD children's ability to efficiently process numerical sequence information when, for example, carrying out complex mathematical calculation. This deficit, in turn, may contribute to the DD group's significantly lower calculation scores, relative to their typically developing peers.

Morsanyi, van Bers, O'Connor and McCormack (2018) matched a group of children with Dyscalculia to a group of controls on several variables (age, gender, socioeconomic status, reading skills and IQ) and assessed groups differences on magnitude and ordinal measures, as well as other measures (e.g. Visuo-spatial WM, Inhibition). Morsanyi et al. found that the groups differed on measures of numerical and non-numerical order, as well as on Number line estimation and Non-symbolic comparison tasks (see Appendix R). Furthermore, Morsanyi et al. carried out a logistic regression to analyse which tasks would be the best predictors of group membership (being characterized as being in the Dyscalculia or control group). The authors found that performance on the Order WM task, and scores on an Order-Processing Questionnaire (see Appendix B), were significant predictors of group membership, along with Number line performance. These measures could be used to correctly identify 80% of participants as either dyscalculic or non-dyscalculic.

Together, these studies provide some of the first evidence that children's ability to process non-numerical order may be an important factor in explaining the deficits exhibited by individuals with DD. This suggests that if order-processing skills are impacted in DD, then this reflects a deficit in a general ability to process order, rather than being a specific numerical deficit. Interventions aimed at improving maths abilities in individuals with DD, therefore, may be useful if they are designed to train children's ordering abilities in general, as these children exhibit difficulties with the processing of both numerical and non-numerical order. These studies also contribute to our understanding of typical numerical development, suggesting that it is possible that non-numerical ordering skills play a pivotal role in the early development of numerical abilities, and that if children show difficulties in these skills, then it is possible that these children will also struggle later with learning mathematics.

2.2.2 Neuropsychological evidence regarding the processing of ordinality in the brain

Evidence from neuropsychological studies concerning numerical and non-numerical order have consistently shown that both are processed via similar brain structures during task performance, suggesting that there may be a set of structures responsible for the processing of order information, regardless of whether the sequence is numerical or non-numerical. Given that numerical ordering skills have been found to be linked to maths achievement in developmental studies, this supports the possibility that non-numerical ordering skills may also be involved in the development of numerical abilities in childhood.

Kaufman et al. (2009) carried out an fMRI study investigating the processing of numerical and non-numerical order in both typically-developing children and children with DD, who were matched on age and

IQ. These participants completed measures of numerical order and size order judgement. The results showed that children with DD were slower and less accurate than their peers, although these differences were not significant. Furthermore, Kaufman and colleagues found that the processing of both numerical and non-numerical order was supported by activation in the intraparietal sulcus (IPS), which has been consistently cited as being involved in numerical processing more generally (e.g. Ansari, Dhital & Siong, 2006; Ansari, Fugelsang & Venkatraman, 2006; Budgen, Price, McLean & Ansari, 2012; Dehaene, Piazza, Pinel & Cohen, 2003; Franklin & Jonides, 2009; Holloway, Price & Ansari, 2010; Knops & Willmes, 2014; Lyons & Ansari, 2009; Lyons, Ansari & Beilock, 2015; Lyons, Vogel & Ansari, 2016; Matejko, Price, Mazzocco & Ansari, 2012; Sokolowski, Fias, Ononye & Ansari, 2017; Venkatraman, Ansari & Chee, 2005; Vogel et al., 2013, 2017; Vogel, Goffin & Ansari, 2015). These results suggest an overlap in the brain areas responsible for the processing of both numerical and non-numerical order, in an area that has consistently been shown to be involved in the processing of numerical information, which shows evidence of an overlap in the processing of numerical and non-numerical order.

The findings of Kaufman et al. are consistent with other research (e.g. Fias, Lammertyn, Caessens & Orban, 2007; Fulbright et al., 2003; Ischebeck et al., 2008; but see Lyons and Beilock, 2013; Zorzi, Di Bono and Fias, 2011) which has also found evidence of similar activation patterns in the processing of numerical and non-numerical order. Fias et al. (2007) found that both Number and Letter ordering measures elicited activation in the horizontal segment of the Intraparietal sulcus (hIPS). Ischebeck et al.

(2008) investigated whether the IPS was involved in non-numerical sequences, using word generation tasks (involving categories such as numbers, animals and months). Ischebek and colleagues found that the IPS was activated to a greater extent when participants generated items in canonical order, compared to word repetition conditions, and that there was greater activation for the generation of numbers and months than for animals. There were no differences in the level of IPS activation for numbers or months when generated in canonical order. Fulbright et al. (2003) found that performance on Letter, Number and Shape ordering tasks elicited activity in the occipital lobes and the IPS.

These studies are suggestive of the processing of numerical and non-numerical order being linked to activity in the IPS, and that even though this area has been suggested as the loci for number processing in general, it appears to process numerical and non-numerical order information similarly. In this thesis, I analysed the link between ordinal measures at the behavioural level, using correlation analysis. Although the non-numerical tasks used in the current study were not the same non-numerical tasks that were used in the studies discussed in this section, nonetheless the pattern of results described earlier would suggest that there should be some evidence of a link between numerical and non-numerical order-processing measures, and that the type of items in these tasks is irrelevant, as long as the focus of the measures is on order-processing skills.

2.2.3 Temporal ordering

Number and Letter ordering tasks are domain-specific measures of order-processing skills, which involve the retrieval of a familiar sequence of items from long-term memory. However, temporal ordering skills are also domain-specific, and the development of children's representations of the temporal order of events has received a considerable amount of research attention (e.g. Friedman, 1977, 1983, 1986, 1989, 1990, 2000a, 2000b, 2002, 2005; Friedman & Brudos, 1988; Zampini, Suttora, D'Odorico & Zanchi, 2013; Zampini et al., 2017), in terms of understanding how children's temporal knowledge develops across childhood, but to the best of our knowledge, temporal ordering skills have not been assessed in relation to mathematical development amongst young children.

Children are introduced to sequences of temporal events (such as a sequence of daily events, the sequence of the days of the week, the sequence of the months of the year and the sequence of the seasons of the year) prior to, and throughout their primary school education. It is argued that even very young children acquire mental representations of repeated sequences of events over multiple time scales during the early years (Fivush & Hammond, 1990; Nelson, 1986, 1998), and that children as young as 4 years old possess spatialized representations of the order of familiar daily events (Friedman, 1977; 1990), suggesting that even very young children can represent the order of familiar everyday events. Similarly, children are able to recall the order of the seasons of the year by age 5-6 (Friedman, 2000a; 2000b), and can reconstruct the correct order of the days of the week and months of the year by age 7-8 (Friedman, 1977)

How do we acquire knowledge of temporal events in the first place? Acquiring and using ordered representations of repeated events forms a crucial part of children's learning about the world, and indeed has been argued to be foundational in cognitive development, as children begin to develop scripts about temporal events, from which children generate expectations regarding the temporal sequence of actions that are linked to a particular spatial-temporal context (Nelson, 1998). There is evidence suggesting that young infants can carry out a sequence of actions in order, for the purposes of reaching a goal (Bauer, 1996). Furthermore, children's mastery of temporal terms (the distinction between *past*, *present* and *future*, as well as the distinction between *before* and *after*) develops during the first five years of life (Friedman, 2000b), suggesting that even young children have some appreciation of temporal aspects of the world around them.

According to Friedman (1989, 2000b), temporal ordering skills can be explained in terms of two different models, which appear at different stages of development; a Verbal-list model and an Image model. The Verbal-list model stores items as a sequential string of names, which allows individuals to activate the order of the sequence of items in memory. The Image model codes spatial information between items, allowing individuals to spatially analyse the proximity and the relative order of items. For sequences such as the order of the days of the week and the months of the year, Verbal-lists for these types of information emerge between the ages of seven and eight, whilst Image representation of the order of the days of the week and the months of the year do not appear until adolescence; however, children as young as four to possess Image representations of the order of familiar daily events, which may develop through their discussion with parents and teachers about what happens throughout their day (Friedman, 2000b). Friedman (1990, 2005) found that young children can judge which daily event comes next in a sequence, judging backwards from different reference points, which further supports the early acquisition of image-based representations of familiar daily events, suggesting that even young children are able to spatially code the order of daily events in long-term memory, allowing them to construct spatialized mental models of daily event sequences. This proposal is further supported by Friedman and Brudos (1988), who argue in favour of a common mechanism for the coding of both spatial and temporal information. These results argue in favour of children's representation of temporal order for familiar, daily event are spatial in nature.

It appears that by age 4-6, children can reliably order a sequence of familiar daily events (Friedman, 1977), suggesting that children are able to master this ability by the end of the Foundation years in primary school/beginning of Key Stage 1. Consequently, it would be very easy for older children to order these familiar events, so one would expect older children to score close to, or at ceiling, on tasks assessing their ability to order familiar daily events. One way to assess temporal order skills in older children is to assess the extent to which they are able to order familiar annual events (such as Christmas, Easter etc.), as children begin to learn the order of annual events from around six and onwards (Friedman, 2000a, 2000b). By age 8-10, children show evidence of mental representations of the order of familiar annual events (Friedman, 2000; 2002), suggesting that older children are able to begin to master this sequence of events.

In the current thesis, I created a Daily events order task (see Figure 2.2) for younger children (based on the same task used by Friedman, 1977) and an Annual event order task (see Figure 2.3) for older children (based on the same task used by Friedman, 2000a). These tasks involved children having to judge whether a triad of events were in the correct forward order, from left to right, within the same day/year (no trials involved crossing a boundary). Although this task is non-numerical, the events in the task can be ordered along a sequence, from left to right, in the same manner as the proposed mental representation of number along the mental number line (or in the case of temporal ordering, a mental time line). Also, the task can be solved in a similar way to the Number order task, as the events can be represented in terms of their ordinal position within the sequence of events (e.g. 'waking up'/'Valentine's day could be represented as '1'). Evidence for the representation of these sequences along a continuum, similar to the mental number line, would be shown if children's performance on the temporal ordering task showed evidence of a reverse distance effect for canonical trials, and a normal distance effect for mixed-order trials[1].

What is the link between temporal ordering skills and the development of numerical abilities? Whilst success in both Number ordering and Daily/Annual event tasks depends on children's ability to map temporal order to spatial order (but see Tillman, Tulagan, & Barner, 2015),

[1] Distance effects could only be assessed on the Annual events task used with older children, as the Daily events task was not created to take into account the 'numerical distance' between the items; on the Daily events task, more attention was paid to ensure that children did not rely on anchor points (such as the last and first event in the sequence) in order to solve the task

Friedman and Brudos argue that 4 year-olds utilize a common mechanism for the coding of both spatial and temporal information, which suggests that this common representational format is activated during mathematical performance, which is consistent with the claim that temporal and numerical order are represented via a mental number/time line (e.g. Bonato, Zorzi, & Umiltà, 2012). However, Berteletti, Lucangeli, and Zorzi (2012) claim that children first develop a representation of numerical order, and that this representation is then applied to other non-numerical sequences. However, these authors studied non-numerical sequences which are acquired at a later stage in formal education than numerical order (the letters of the alphabet and the months of the year), sequences which young children would find difficult to correctly order. For example, whilst children age 4 are able to order familiar daily events, they cannot reliably order the seasons of the year until 5-6 years old, and between 7-8 years old for ordering days of the week and months of the year (Friedman, 1977; 2000a; 2000b). Given that number ordering skills have been linked to numerical development, but only from the age of six onwards (e.g. Attout & Majerus, 2018; Attout et al., 2014; Lyons et al., 2014; Sasanguie & Vos, 2018), and that there is a possible link between temporal, spatial and numerical processing (e.g. Friedman & Brudos, 1988; Walsh, 2003), it is plausible that children's temporal ordering skills may be in place before they learn about the order of the symbolic numbers. It may be the case that these skills (which are apparent even from as young as 4 years old) are a template for the building of mental representations of numerical order, which would suggest that these skills play a pivotal role in early numerical development. However, as numerical ordering skills emerge in their importance, temporal ordering skills may no longer be important to mathematical development from around the age of six, so it could be the case that these skills no longer play an important role in mathematical development amongst older children.

There may also be a link between the underlying mechanisms responsible for the processing of temporal order, and the development of children's language skills, which also suggests that order-processing skills may be involved in the development of other academic skills. Recently, temporal ordering skills have been examined in relation to language development by some authors. Work by Laura Zampini and colleagues into children's sequential reasoning skills (Zampini, et al., 2017; Zampini, Suttora, D'Odorico & Zanchi, 2013) has used a production task, which are somewhat similar to the Daily and Annual events tasks used in this thesis (the tasks used in this thesis were verification tasks, but the training tasks used prior to children engaging in the Daily events task were production tasks). Zampini and colleagues' work (Zampini, et al., 2017; Zampini, Suttora, D'Odorico & Zanchi, 2013) found that performance on a Sequential Reasoning Task (SRT), which involved putting together the correct forward order of a set of cards which depicted a sequence of events (each set contained 3, 4 or 5 cards), was related to listening comprehension and language development. The results suggest that this task, which has a strong ordering component to it, was related to academic skills other than mathematics, which opens up the possibility that order-processing skills may also be involved in the development of other academic skills in childhood.

As well as assessing the extent to which temporal ordering skills may play an important role in early numerical development, I also assessed the extent to which order-processing skills were related to the development of reading skills amongst older children, to ascertain whether order-processing skills also play a role in the development of other academic subjects.

Figure 2.2. Example of a canonical trial in the Daily events task

Figure 2.3. Example of a canonical trial (with a numerical distance of 2) in the Annual events task

2.2.4. Order-processing skills involving familiar everyday tasks

Efficient order-processing skills may also be important for young children to perform everyday tasks, such as learning how to dress themselves for school, which involves them learning how to put clothes on in the correct order (e.g. putting a shirt on before putting a jumper/blazer on), and learning how to carry out an ordered sequence of actions to achieve an end goal (e.g. carrying out the subsequent steps to put on a tie correctly, or to put on and tie a pair of shoes). Indeed, as previously mentioned, even young infants utilise ordering skills to reach an end goal (Bauer, 1996). Order-processing skills may also be involved in children being able to recall information from long-term memory, in the correct order (e.g. recalling the correct order of a sequence of past events).

There is evidence from clinical reports of Developmental Dyscalculia (DD), which suggests that children with this disorder may have problems in carrying out sequential actions in order to reach a goal (National Centre for Learning Disabilities, 2007). In their report on Dyscalculia, the National Centre for Learning Disabilities (NCLD) report several areas in which children with DD may have difficulties with (aside from issues relating directly to mathematics). Interestingly, some of these areas may rely on order-processing skills. For example, the NCLD report that children with Dyscalculia may have difficulty with the concept of time; they may often be late, underestimate or overestimate the duration of an activity, and may also have difficulty in remembering schedules. The NCLD also report that children with DD may also suffer from a poor sense of direction, may be easily disorientated and may be easily confused by changes in routine. This suggests that the deficits shown in DD are not only related to mathematics, but also have far-reaching consequences outside of the classroom environment, and may affect children's ability to effectively carry out familiar everyday tasks.

If it is these types of skills which are affected in DD, and given that children with DD exhibit problems with mathematics, and earlier evidence has suggested that these deficits may be related to non-numerical ordering skills (Attout & Majerus, 2015; Morsanyi, Devine, Nobes & Szűcs, 2013; Morsanyi, van Bers, O'Connor & McCormack, 2018), it may be the case that these skills may also be involved in the development of numerical abilities amongst typically-developing children. However, the extent to which parents believe that their children have an adequate grasp of these skills has not been addressed in the research literature, with the exception of a study that I co-authored (Morsanyi, van Bers, O'Connor & McCormack, 2018), which found that everyday ordering skills were an important predictor of a DD diagnosis, suggesting that this questionnaire may be a useful diagnostic tool in detecting children who may have problems with mathematics.

Consequently, I was interested in investigating the extent to which parents of younger and older children agreed with statements concerning their child's ability to perform everyday tasks (which had some order-processing component to them), as this questionnaire may be able to detect children who may be struggling with mathematics, in the beginning and towards the end of primary school. To this end, I created two versions of a questionnaire aimed at assessing children's everyday ordering abilities, which I called the parental Order-Processing Questionnaire (OPQ; these questionnaires are included in Appendices A and B respectively). Low scores on the items on this questionnaire would reflect possible difficulties with carrying out everyday order-processing tasks, which might be an indicator of potential mathematical difficulties, given that these symptoms have been observed in children with DD.

2.2.5 Working Memory measures

As discussed in Chapter 1, working memory (WM) updating skills appear to be involved in numerical development; Visuo-spatial WM skills have been suggested to be more important to the development of maths skills amongst younger children (e.g., Passolunghi, Cargnetti & Pastore, 2014; Passolunghi & Costa, 2014; Soto-Calvo, Simmons, Willis & Adams, 2015; Szűcs, Devine, Soltèsz, Nobes & Gabriel, 2013; Van der Ven et al., 2013), although it is also possible that these skills are also important for older children, but that they are either overshadowed by verbal skills, or that they may be activated during performance of particular mathematical problems (De Smedt et al., 2009; McKenzie, Bull & Gray, 2003; Rasmussen & Bisanz, 2005). The importance of Verbal WM skills in numerical development appear to emerge at developmentally later stages than for Visuo-spatial WM skills (De Smedt et al., 2009; Rasmussen & Bisanz, 2005; but see Attout et al., 2014). In the following subsections, I will discuss the evidence in support of the role of both skills in the development of numerical abilities, focusing on the respective Visuo-spatial and Verbal WM tasks that were included in this thesis.

2.2.5.1 Visuospatial WM

One of the Visuo-spatial WM measures which has been used in mathematical cognition literature is the Backward matrices task (e.g. Mammarella, Hill, Devine, Caviola & Szűcs, 2015), in which participants are shown a sequence of blue squares, appearing in different parts of a matrix, and they have to remember and re-create this pattern, but in backwards order (see Figure 2.4). This measure was based on a task used in other studies that have assessed the relationship between working memory and intelligence (Giofré, Mammarella & Cornoldi, 2013; Hornung, Brunner, Reuter & Martin, 2011), in which children had to remember and re-create the sequence of visually-presented stimuli, which were presented either on a grid or against a blank screen. Mammarella et al. (2015) used a backward matrices task in their study of adolescents with Developmental Dyscalculia and Mathematical Anxiety, and found that children in the Dyscalculia group performed significantly worse on this task compared to a group of typically-developing children who were matched to the Dyscalculia group on reading, IQ and general anxiety. This finding is supported by Morsanyi and colleagues (Morsanyi, van Bers, O'Connor & McCormack, 2018), who found that 8-11-year-old children with DD had a significantly lower order memory span in the Backward matrices task than controls (matched on age, gender, socio-economic status, educational experiences, IQ and reading ability), but the two groups did not differ on task accuracy.

This task has also been adapted for use in computer-based mathematical learning programs, such as Math Garden, which is an adaptive web-based mathematical program for children (e.g. van der Ven, Klaiber &

van der Maas, 2017; van der Ven, van der Maas, Straatemeier & Jansen, 2013). One of the games within Math Garden (the Mole game) is a Visuo-spatial WM task, involving the re-creation of sequences in forwards or backwards order. Van der Ven et al. found that performance on this game was a strong significant predictor of younger children's addition and subtraction performance. There was also a decreasing age trend, whereby the mole game explained less variation in addition and subtraction performance for the oldest children in this subgroup.

These results suggest that poor Visuo-spatial WM skills may be linked to DD and that lower performance on this task may be related to lower mathematical achievement within a typical sample. Given that these results were found for older children, the Backward matrices task was only used with older children in the sample, to investigate whether these skills play an important role in later mathematical development.

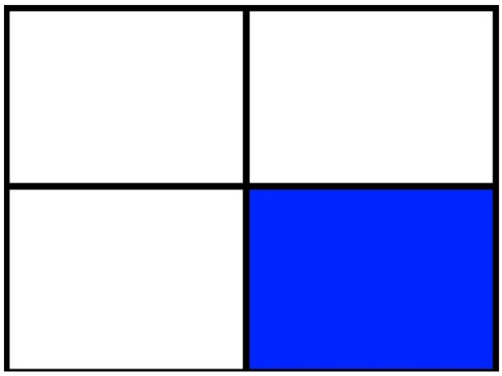

Figure 2.4. Example of one of the illuminated squares during a trial in the Backward matrices task

2.2.5.2 Verbal WM

The serial reconstruction task (Majerus, Poncelet, Greffe & Van der Linden, 2006), otherwise known as the Order WM task (Attout & Majerus, 2015; Attout, Nöel & Majerus, 2014), assesses children's ability to retain and re-create serial order information after a short-term retention delay (see Figure 2.5). In the task, children listen to an audio sequence of monosyllabic animal names (ranging from 2-7 animal names) and have to re-create the correct order that they had heard, using cards which depict the animals. This task had previously been used in studies of literacy development and there is evidence to show that performance on this task has been found to predict children's vocabulary development (Leclerq & Majerus, 2010; Majerus et al., 2006, 2009); novel word-learning ability (Majerus & Boukebza, 2013); and reading acquisition (Martinez Perez, Majerus & Poncelet, 2012). Success on this task is dependent upon the extent to which children can maintain the correct order of an arbitrary sequence, and then retrieve it accurately from short-term memory, thus this task measures order-processing skills that are perhaps different from those involved in the retrieval of familiar content from long-term memory (as measured by Number ordering, Daily/Annual events and the OPQ).

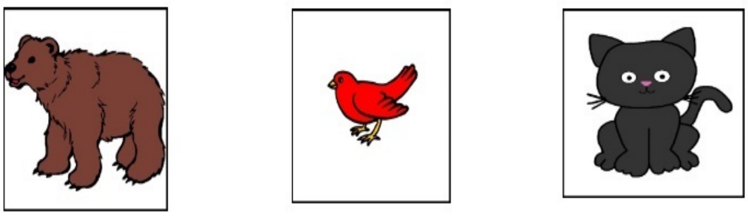

Figure 2.5. Example of three of the stimuli used in the Order WM task

Studies of typical and atypical mathematical development have found a link between task performance and mathematical achievement. For example, studies have shown that older children with DD perform significantly worse on this task, when compared to controls (Attout & Majerus, 2015; Morsanyi, van Bers, O'Connor & McCormack, 2018), which suggests that Verbal WM skills are also affected by DD. Several studies of typical mathematical development (e.g. Attout & Majerus, 2018; Attout et al., 2014) have also investigated the role of Order WM in numerical development. Attout et al. tested children in Kindergarten (T1; aged 5-6 years old), in 1st grade (T2; aged 6-7 years old) and in 2nd grade (T3; aged 7-8 years old). Order WM performance concurrently correlated with arithmetic performance at each time-point (except for the simple calculation at T3). Furthermore, Order WM performance at T1 longitudinally correlated with arithmetic one and two years later. Attout and Majerus (2018) also found that Order WM performance amongst 7-9-year-olds was related to arithmetic performance, although this link was mediated by Number ordering performance. These results suggest that for young children, Order WM abilities reliably and independently predict arithmetic abilities, but this is not the case for older children, which suggests that older children may rely less on temporary maintenance of the number sequence in WM, in comparison to younger children.

To assess the relative importance of Verbal WM skills in numerical development, this task was used in both studies. Given the evidence discussed earlier, it was predicted that Order WM abilities would be related to mathematical achievement across development. However, given that I used a different age range than Attout and Majerus (2018), which included children who were preparing to finish primary school, it could be the case that Order WM may be even more strongly related to mathematical achievement amongst these children, given that older children may rely more on verbal skills when performing mathematics (Attout & Majerus, 2018; Attout et al., 2014).

2.3 Limitations of the existing literature

The evidence regarding a link between ordinality and maths development is quite promising. However, there are some limitations to the current literature, which I aim to address in this thesis. One of the main issues concerns the lack of research investigating the development of numerical abilities in very young children. As mentioned in the previous chapter (see Chapter 1, Table 1.2), and in this chapter, Northern Ireland has one of the youngest school starting ages in the world (Eurydice at NFER, 2013), with children beginning school on the first September after their 4th birthday, which would make the sample in Study 1 the youngest school-age sample tested in the world, in the field of mathematical cognition. Study 1 aimed to address the question of which skills are important to early numerical development by testing children in their first year of primary school, to assess the relative contribution of order-processing skills to numerical development amongst a sample of very young children, as well as with children who are preparing to leave primary school, given that many other studies of order-processing have not included children up to this point in development.

Another limitation concerns the use of arithmetic as a measure of children's numerical development (e.g. Attout & Majerus, 2015; Attout & Majerus, 2018; Attout et al., 2014; Lyons et al., 2014; Sasanguie & Vos, 2018). Although arithmetic skills are an important part of mathematics (Geary, 1993), the Northern Ireland curriculum, for example, consists of a number of different areas which are important for mathematical learning (see Chapter 1, Table 1.1). It is possible that the cognitive tasks used in studies, which have indexed mathematical performance using arithmetic, are only explaining variance in (or are significantly correlated with) a narrow subset of mathematical learning, and fail to take into account other aspects of the mathematical curriculum. In the experimental chapters, I included standardized, curriculum-based measures of mathematical achievement. Using these tests not only made it possible to identify the significant correlates and predictors of mathematical achievement amongst young and older children, but also allowed for correlations to be run between the different mathematical components and each of the cognitive measures, allowing for a clearer picture as to exactly which measures are related to each aspect of the school mathematics curriculum.

Another limitation concerns the lack of longitudinal research on order-processing skills. So far, Attout et al. (2014) are the only authors who have conducted a longitudinal study of order-processing skills with young children. However, these authors a) did not include a measure of non-symbolic magnitude, b) measured maths achievement using arithmetic, and c) only included Order WM and Number ordering measures as their ordinal tasks. In the current thesis, Study 1 aimed to build on the work of Attout et al. by a) including the Non-symbolic addition task as a measure of the ANS, b) including a standardized measure of mathematical achievement, and c) also including two additional order-processing measures, the Daily events task and the OPQ. Study 1 also included children who were over 1 year younger than the sample in the Attout et al. study, making them one of the youngest school-age samples to be tested in the domain of order-processing skills.

2.4 Issues to be addressed regarding the role of ordinality in numerical development

In the following subsections, I will discuss the issues that the current thesis aims to address, with respect to the specific issues surrounding the role of ordinality in the development of numerical skills across childhood.

2.4.1 Is ordinality predictive of maths achievement across development? If so, when does ordinality become important to maths? Is it more important to maths than magnitude (or estimation)?

There are now several studies which have directly compared the contribution of both ordinality and magnitude to maths development. Based on the existing evidence, it is now beginning to emerge that order-processing skills a) are predictive of maths achievement, b) are important to numerical development right from the beginning of primary school, and c) are better predictors of numerical abilities than magnitude.

For example, several studies have now shown that order-processing skills are a stronger predictor of mathematical achievement than magnitude skills (e.g. Attout & Majerus, 2018; Attout et al., 2014; Lyons & Beilock, 2011; Lyons et al., 2014; but see Vogel et al., 2015), which also calls into question the importance of the ANS to numerical development. Magnitude and ordinal skills have also been compared in studies of children with Developmental Dyscalculia. Morsanyi, van Bers, O'Connor and McCormack (2018) found that two order-processing measures (scores on an Order-Processing Questionnaire and Order WM scores) were significant predictors of whether a child would be classed as being in the Dyscalculia group or in the control group. Neither Symbolic nor Non-symbolic comparison tasks were significant predictors of group membership. However, Attout and Majerus (2015) found that 8-12-year-olds with DD performed worse on Number comparison and Number ordering tasks (but not on Non-symbolic comparison), but also showed deficits in Order WM performance. These results also suggest that order-processing skills may be more affected by DD than magnitude, questioning the assumption that problems with processing magnitude are the main cause of the numerical problems that are evident in individuals with DD (e.g. Piazza et al., 2010). Whilst it is possible that problems with processing magnitude may still be a core feature of the disorder, these findings suggest that deficits in these skills may not necessarily be the biggest problem for individuals with DD.

However, another possibility (e.g. Sasanguie and Vos, 2018) is that the importance of magnitude and ordinality to numerical development may emerge at different stages, especially given that it has been proposed that knowledge of the magnitude of the number system emerges before ordinal knowledge (Michie, 1985). By assessing the relationships between the cognitive measures and maths achievement at the cross-sectional level (in Study 1 when children are aged 4-5, and when they are aged 5-6; in Study 2, when children are aged 8-11), I can identify which measures are important to maths development at each stage, as well as identifying which measures can explain variance in maths achievement at each stage as well.

As mentioned previously, number ordering skills have been linked to numerical development, but only from the age of six onwards (e.g. Attout & Majerus, 2018; Attout et al., 2014; Lyons et al., 2014; Sasanguie & Vos, 2018), which suggests a specific point in development when these skills emerge as an important factor in the development of maths skills, although the findings of Attout et al. suggest that Order WM performance may play an important role in numerical development amongst children as young as 5. Since Study 1 involved children aged as young as 4, the analysis of which cognitive measures would be important to maths achievement at the end of their first year of primary school would address the question of whether order-processing skills are involved in early numerical development amongst a sample of very young school-age children.

The existing literature regarding Number line estimation suggests that estimation skills are related to numerical development, even in children as young as three (e.g., Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Booth & Siegler; 2006, 2008; Link et al., 2014; Schneider et al., 2018; Siegler & Booth, 2004). A meta-analysis of the link between Number line performance and mathematical achievement (Schneider et al., 2018) found that the effect sizes increased with age (.30 for under 6's; .44 for 6-9-year olds and .49 for 9-14-year-olds). This is supported by the findings of a review, (Schneider, Thompson & Rittle-Johnston, 2017), which found that the relationship between Number line estimation and maths achievement is stronger than the relationship observed between maths and Number comparison amongst studies of children aged 6 and above (but similar for children younger than 6). However, Lyons et al. (2014) found in their study that Number line performance was a strong predictor of early arithmetic achievement, but that it was overshadowed by the increasing importance of Number ordering skills from age 9 and onwards. Together, these results suggest that estimation skills may be more strongly related to numerical development amongst children who have already had some experience of formal maths learning, but that it may become less important amongst older children when compared to Number ordering abilities. Therefore, it is reasonable to predict that Number line performance would be related to maths achievement throughout development in this thesis, but that Number ordering skills would come to the fore for older children in terms of their relative importance to numerical development.

2.4.2 Is the link between ordinality and maths achievement restricted to numerical ordering skills?

We do not yet fully know the precise nature of the order processing skills that are important for maths development. More specifically, less is known about the role of non-numerical ordering skills in the development of maths abilities in children, compared to numerical ordinal skills.

As previously mentioned, there is some emerging evidence of a link between non-numerical ordering abilities and typical and atypical numerical development (e.g. Attout et al., 2014; Morsanyi, van Bers, O'Connor & Morsanyi, 2018). This link has also been observed in studies of adults (Morsanyi, McCormack & O'Mahony, 2017; Morsanyi, O'Mahony & McCormack, 2018; Vos, Sasanguie, Gevers & Reynvoet, 2017). As previously mentioned, I included the Order WM task (Attout et al., 2014; Majerus et al., 2006) as performance on this task has been found to be linked to numerical development. However, I was also interested in investigating the ability to process order information regarding familiar non-numerical sequences held in long-term memory, by introducing two types of non-numerical ordering measures that have not been used previously in the literature.

Two temporal ordering tasks (the Daily events and Annual events task), inspired by previous research with young children (Friedman, 1977; 1990; 2000) were employed, which is similar to the number ordering tasks used in other studies (e.g., Lyons & Ansari, 2015), except that children were shown three daily/annual events, rather than three numbers. The task is also similar to month ordering tasks that have been used in adult studies (e.g., Morsanyi et al., 2017; Vos et al., 2017), with the exception that the time frame in the Daily events task is much shorter; the Daily/Annual events tasks involves the presentation of triads of events which happen during one day/year, whilst the month ordering task involves the presentation of three months that occur throughout one calendar year. In the Daily events task, each test trial was drawn from a set of six familiar daily events (waking up, getting dressed, going to school, eating lunch, eating dinner and going to bed), whilst in the Annual events task, each test trial was drawn from a set of nine familiar annual events (your birthday, Valentine's day, Easter, school sports day, summer holidays, going back to school, Halloween, Christmas day and New year's eve), and children judged whether the order of the events was correct or not.

Second, to assess the role of everyday non-numerical ordering skills, I developed a new questionnaire (OPQ: Order-processing Questionnaire) to assess the extent to which parents agreed or disagreed that their child could carry out familiar tasks that all included a requirement to follow a set order (such as getting dressed for school). There was an eight-item questionnaire for young children, and a seven-item questionnaire for older children. The motivation for using this measure was the existence of clinical reports of individuals with developmental dyscalculia that describe how they often struggle with everyday tasks that have a strong ordering component, such as being confused by changes in their everyday routine (National Center for Learning Disabilities, 2007). Together, these tasks provided a novel way of assessing the relation between domain-general order processing abilities and emerging maths skills.

This thesis is the first to use several non-numerical ordering measures and was the first within the mathematical domain to use tasks that measured children's ability to process order for familiar sequences and for familiar events. As proposed earlier, there may be a link between temporal, spatial and numerical processing (e.g. Friedman & Brudos, 1988; Walsh, 2003). Even though numerical ordering skills do not appear to emerge in their importance to numerical development until age 6 (almost two years after children in Northern Ireland begin school), children already possess spatialized representations of the order of familiar events (Friedman & Brudos, 1988). I propose that temporal ordering skills act as a template for the future representation of the number sequence, which would suggest that these skills may play a pivotal role in early numerical development.

However, as numerical ordering skills emerge in their importance, temporal ordering skills may no longer be important to mathematical development amongst older children, as they may by this stage have begun to automatize the number system. Also, Order WM was found to be related to maths amongst older children (Attout & Majerus, 2018), suggesting that perhaps older children begin to employ verbal strategies when solving maths problems. Based on this, I predict that Order WM abilities will emerge in their importance to numerical development amongst older children, at the same time that Number ordering also becomes more strongly related to maths achievement, whilst temporal ordering skills will decline in terms of their importance amongst 8-11-year-olds.

2.4.3 How are ordinal measures related to each other? How are magnitude measures related to ordinal measures?

Regarding the link between ordinal measures, Attout et al. (2014) found that Order WM performance did not correlate with Number order performance between the ages of 5 and 8. Furthermore, performance on Number order and Order WM tasks showed different patterns of relations with arithmetic, suggesting that that they draw on different order processing skills and might be related to maths skills for different reasons. For example, they both differ in terms of their content (numerical vs. non-numerical), the memory system from which information is retrieved (short-term vs. long-term memory) and in terms of the familiarity of the sequence (familiar sequences vs. arbitrary, novel sequences). However, Attout and Majerus (2018) found that Order WM and Number order tasks were related, even after controlling for age, non-verbal reasoning, and vocabulary knowledge, amongst 7-9-year-olds, perhaps reflecting the development of stronger general order-processing mechanisms for older children. Based on these findings, I predicted that for young children, Number order and Order WM would be unrelated, but that these measures would become more strongly related amongst older children.

The links between the OPQ, Daily/Annual events measures and other ordinal tasks have not been investigated so far in the case of young children. However, some predictions can be made on the basis of the findings of Morsanyi and colleagues (Morsanyi, van Bers, O'Connor & McCormack, 2018). The authors found that the OPQ was not related to any of the ordinal measures, although there were weak correlations (but still non-significant) between OPQ scores and both Annual events and Number ordering measures. Annual events performance was related Visuo-spatial WM, and strongly related to Number ordering. These results support the proposal that numerical and temporal ordering skills are related. Based on these results, I predicted that OPQ and Daily/Annual events measures would correlate with each other, and with Number ordering, in both young and older children.

There is evidence to suggest that numerical ordinal and numerical magnitude skills are related to each other, which suggests that there may be a certain degree of overlap regarding the systems responsible for the processing of magnitude and ordinality. Lyons et al. (2014) found that across all participants and all grades, Number Ordering performance was significantly correlated with performance on Number comparison. Attout et al. (2014) found that Number order and Number comparison performance were significantly correlated at each time point. Attout and Majerus (2018) also found a strong correlation between Number order and Number comparison performance amongst 7-9-year-olds. Furthermore, Sasanguie and Vos (2018) found significant correlations between number comparison and number ordering performance in grade 1 and grade 2. These results suggest that the mechanisms for processing magnitude and ordinal information with regard to numbers shows some degree of overlap across childhood. Consequently, I predicted that numerical ordering and numerical magnitude skills would be related across childhood.

Whilst Order WM performance was uncorrelated with Number comparison abilities for younger children (Attout et al., 2014), they were significantly related amongst 7-9-year-olds (Attout & Majerus, 2018), but not amongst 8-11-year-olds (Morsanyi, van Bers, O'Connor & McCormack, 2018). Morsanyi and colleagues also found that Annual event ordering was related to Number comparison performance. These results suggest some evidence of a relationship between non-numerical ordering and symbolic magnitude-processing skills. Regarding the relationship between non-symbolic magnitude and symbolic ordinal measures, significant relationships have been found between Number order and Dot comparison measures (Lyons et al., 2018; Morsanyi, van Bers, O'Connor &

McCormack, 2018). Similarly, non-symbolic magnitude has also been linked to Order WM performance (Morsanyi, van Bers, O'Connor & McCormack, 2018). One explanation for this finding could be that although the proposal that the ANS is an important building block of mathematical development is quite controversial, nonetheless the ANS may be an important building block of ordinal skills (such as Number ordering), which could be considered to be even more important to maths development than the ANS. As a result, I predicted that non-symbolic magnitude measures would be related to numerical and non-numerical order-processing measures across development.

Chapter 3: The role of numerical and non-numerical ordering skills to maths development at the beginning of formal education

3.0 Introduction

As discussed in the previous chapter, there has been an increasing interest in the link between ordinality and mathematical skills, and many studies have found evidence of such a relationship in studies with adults (e.g., Lyons & Beilock, 2011; Morsanyi, O'Mahony & McCormack, 2017; Sasanguie et al., 2017; Vos et al., 2017) and in developmental studies of both typical and atypical populations (e.g., Attout, Noël, & Majerus, 2014; Attout & Majerus, 2015, Lyons et al., 2014; Morsanyi et al., 2013; Morsanyi, van Bers, O'Connor & McCormack, 2018). However, there are several questions surrounding this relationship (outlined in Chapter 2) that have not yet been adequately answered. In the following, I will also discuss the issues that are pertinent to this particular study, as well as proposing how each of these issues will be addressed in the study.

3.1 Study 1

3.1.1 Which skills predict maths during the first years of primary school?

Previous research (e.g. Chen & Li, 2014; Fazio et al., 2014; Schneider et al., 2016) has suggested that the ability to process magnitude plays an important role in children's early learning about maths. Particularly, researchers argue that the ANS acts as a precursory step between approximate and exact arithmetic skills, and so plays an important role in the subsequent development of mathematical abilities in the early years of school. However, both meta-analyses and review papers have shown that symbolic magnitude-processing skills are a better predictor of maths, compared to non-symbolic magnitude, in studies involving school-age children (e.g., De Smedt, Noël, Gilmore & Ansari, 2013; Fazio, Bailey, Thompson & Siegler; Schneider et al., 2016). Furthermore, there are both methodological and reliability issues concerning the dot comparison task, which has been one of the most widely-used measures of the Approximate Number System in mathematical cognition literature (e.g., Inglis & Gilmore, 2013, 2014; Maloney et al., 2010; Price, Palmer, Battista and Ansari, 2012). This casts doubt upon the assumption that non-symbolic magnitude skills, which are thought to reflect the accuracy of the Approximate Number System, are the sole precursor to the development of a more sophisticated system for exact symbolic number processing (e.g., Chen & Li, 2014; Piazza et al., 2010). Furthermore, the finding that performance on symbolic and non-symbolic magnitude measures (e.g., Holloway & Ansari, 2008; Maloney et al., 2010; Morsanyi, van Bers, O'Connor & McCormack, 2018; Sasanguie, De Smedt, Defever & Reynvoet, 2012) suggests that the mechanisms underlying the processing of exact and approximate magnitude-processing skills may be unrelated, further casting doubt upon the role of the ANS in early numerical development

However, another factor which has emerged as a target of recent research interest is ordinality. Much like magnitude, ordinality is an important property of numbers, and one of the core counting principles set out by Gallistel and Gelman (1978), which states that any set of items to be counted must be counted using the count words in a specific order. Indeed, there is evidence to suggest that the ability to process numerical order is strongly related to maths amongst children aged 6 and above (e.g., Attout & Majerus, 2015; Attout et al., 2014; Lyons et al., 2014; Sasanguie & Vos, 2018). Sasanguie and Vos (2018) found that there was a shift in strategies for solving arithmetic between first and second grade, as they found that number comparison performance fully mediated the relationship between symbolic ordering skills and maths at age 5-6. In contrast, symbolic ordering performance fully mediated the relationship between number comparison and maths at age 6-7. Furthermore, Lyons et al. (2014), found that at the beginning of formal education (at around the age of 7), number comparison and number line performance were the strongest predictors of maths, whilst number ordering did not emerge as an important predictor until age 9. Together, these results suggest that at the beginning of school, symbolic magnitude may be an important contributor to children's formal maths learning, whilst numerical ordering may not emerge as an important predictor until at a later stage.

However, age differences across studies is an important factor which must be taken into consideration. Children began the current study aged between 4-5 years old, which makes them the youngest sample so far in which the link between order processing skills and maths ability has been investigated. The current study was conducted with a sample of children from Northern Ireland, which has the youngest school starting age (4 years old) of all the 37 countries participating in Eurydice, the information network on education in Europe (Eurydice at NFER, 2012), and one of the youngest school starting ages in the world.

The aim of the current study was to follow a sample of children, through their earliest years of education, to adequately address whether ordering skills were important to numerical development and, if so, when do they become important. This involved considering the role of both numerical and non-numerical ordering skills in early maths development (see Figure 3.1), which Lyons et al. (2014) and Sasanguie and Vos (2018) did not investigate in their studies. Attout et al. (2014) carried out the only other longitudinal study of ordinality in a sample of young children and found that non-numerical ordering skills (as measured by the Order WM task) were concurrently related to maths at ages 5 (T1), 6 (T2) and 7 (T3). Furthermore, performance on this task at T1 was longitudinally correlated with maths ability two years later. The children in the current sample would be the same age as the youngest children in the Attout et al. sample, at the end of the current sample's first year of primary school. Given the findings of Attout et al., it was hypothesized that children's ordering skills would predict children's maths achievement at the end of their first year of school.

Whilst Attout and colleagues included a measure of non-numerical ordering skills, an important point is that the ordering skills measured by the Order WM task involve the retrieval of a novel, arbitrary sequence from short-term memory. Whilst the Number ordering task (which Attout et al. also included in their study) involves the retrieval of a familiar sequence from long-term memory (the number sequence), I also included two measures which involve the retrieval of a familiar sequence from long-term memory, but that did not include numbers. I included a short questionnaire, given to parents, which was designed to assess children's ability to retrieve the sequence of familiar everyday tasks from long-term memory. I also included a temporal ordering task, based on previous research (Friedman, 1977; 1990) which assessed children's ability to retrieve the order of a familiar sequence of daily events from long-term memory. This is the first study of mathematical development which has used such measures.

There is now a growing amount of evidence suggesting a link between numerical and temporal processing (e.g. Ben-Meir, Ganor-Stern & Tzelgov, 2012, 2017; Bonato, Saj & Vuillermier, 2016; Casarotti, Michielin, Zorzi & Umiltà, 2007; Hubbard et al., 2005; Oliveri et al., 2008; Schwarz & Eiselt, 2009; Skagerlund & Träff, 2016). More specifically, a proposed link has been proposed, by some authors, between the ability to process order for both numerical and temporal information (e.g. Ganor-Stern, 2015; Magnani & Musetti, 2017), suggesting that there may be a certain degree of overlap between the processing of the order of time and numbers. Indeed, it has been claimed that temporal and numerical order both are represented via a mental number line (e.g. Bonato, Zorzi, & Umiltà, 2012), which suggests the possibility that temporal ordering skills may support the early development of the representation of number along the mental number line. The role of temporal ordering skills as a template for the representation of the number sequence therefore, could be considered pivotal in the mastery of early numerical skills.

Given this proposal, I predicted that ordering skills involving the retrieval of familiar sequences from long-term memory (the Order-

Processing Questionnaire and the Daily events task), would play an important role in early numerical development. Although the results of Sasanguie and Vos (2018) would predict that magnitude skills would initially be more important to numerical development at the beginning of school than ordinal skills, the current study differs to theirs in two respects; a) the children tested in their first year of primary school are 1-2 years younger than the children in grade 1 in their study, and b) those authors did not assess non-numerical ordering skills.

I predicted that symbolic and non-symbolic magnitude skills would be related to early numerical development (at the beginning of primary school), given that these measures have traditionally been found to be linked to maths achievement. However, I predicted that these measures would not be as important to the early development of numerical skills as the ordering measures for familiar content, which would suggest that they play a lesser role in the mastery of the symbolic number system than had previously been thought. However, I did predict that magnitude skills would become more strongly linked to maths achievement at the end of children's second year of primary school. This finding, coupled with a lesser importance of magnitude-processing skills over 1 year earlier, would provide evidence of school experience leading to an improvement in ANS skills, rather than vice-versa.

3.1.2 How strong are the correlations between T1 and T2 for both ordinal and magnitude tasks?

By assessing the strength of correlations between performance at T1 and T2 on each task, one can identify whether the measures included in the study were stable measures of individual differences in basic maths skills. Low correlations between the same measures at both time points would suggest that the skill in question may be undergoing rapid development, whilst strong correlations would suggest that the particular skill has already been developed, and children may be using the same strategy to solve the task across development. This is not to say that performance on the task would not improve with development, but these changes are quantitative rather than qualitative. If this is the case, the task could offer a solid foundation for early maths development. In the Attout et al. (2014) study, analysis of the correlations between measures at T1 and T2 (when children were aged between 5 and 7) revealed that order WM at both time points was strongly correlated (r = .58). Ordinal numerical judgement at both time points was moderately related, as were magnitude judgement tasks at both time points. This suggests that non-numerical ordering abilities may play an important role in early maths development, even in comparison to numerical ordinality and magnitude.

Based on these findings, it is possible that numerical skills are only developing in the early years of school, therefore the way in which children solve mathematical problems may also be changing at this point. Concerning the role of non-symbolic magnitude-processing skills, if they are indeed the foundation of basic maths skills (as many researchers have previously claimed), then they should be well-developed at this point, and therefore should be strongly correlated.

3.2 Method

3.2.1 Participants

Ninety children at the start of their first year of primary school education were recruited from four schools in the Belfast area (43 females, Mean age = 4 years 11 months; *SD* = 3.73 months). Eighty-seven children completed the maths assessment (43 females, Mean age = 6 years 2 months, *SD* = 3.44 months) at the end of their second school year. Due to the demographics of the population in Northern Ireland, the majority of children were of Caucasian origin; information on their SES is reported below.

3.2.2 Materials

Deprivation measure. Children's level of socio-economic deprivation was determined using the Northern Ireland Multiple Deprivation Measure (Northern Ireland Statistics and Research Agency, 2010). This measure assigns a deprivation score to each electoral ward in Northern Ireland based on a variety of indices. A higher score indicates a higher level of deprivation for the area. The scores can be interpreted as percentiles (e.g., a score of 10 means that the area is less deprived than 90% of all postcode-based areas within Northern Ireland). In the current sample, deprivation scores ranged from 1.85 – 68.57 (Median = 11.00). One child did not provide a postcode, so a deprivation score could not be calculated. Along with age and both verbal and non-verbal intelligence, children's deprivation scores were used as covariates in the data analysis.

IQ. Children's intelligence was measured using the Vocabulary and Block Design subtests of the Wechsler Preschool & Primary Scale of Intelligence - Third UK Edition (WPPSI-III UK; Wechsler, 2003). Children's estimated full-scale IQ scores were computed following the method outlined in Sattler and Dumont (2004) and were found to be within the normal range (Mean IQ score = 95.92, *SD* = 13.51).

Baseline reaction time. Based on Fry and Hale (1996), this task involved children responding to the appearance of a red or a green circle by pressing their respective buttons on the screen. Children were instructed to respond as quickly and as accurately as they could. A fixation cross appeared for 1000 ms before each trial. There were 40 trials in this task and children's mean reaction time was the dependent measure. Reliability estimates for this measure were found to be quite high (T1; Cronbach's Alpha = .92. T2; Cronbach's Alpha = .87).

3.2.2.1 Order processing measures.

Parental Order Processing Questionnaire (OPQ). Parents were asked to complete an eight-item questionnaire (included in Appendix A) in which they indicated on a 7-point Likert scale the extent to which they agreed or disagreed with certain statements regarding their child's ability to perform everyday tasks that involved an order processing element (e.g., "my son/daughter can easily recall the order in which past events happened").

The items were developed based on clinical observations regarding the everyday difficulties that individuals with dyscalculia commonly encounter (National Center for Learning Disabilities, 2007), but they were modified to be appropriate for young children. Five items were scored positively (i.e., higher scores indicated better ordering ability), and 3 items were scored negatively. A principal component analysis with varimax rotation showed that the scale had a 2-factor structure, with the positive items loading on factor 1 (which explained 41% of the variance), and the negative items loading on factor 2 (which explained 21% of the variance). The scale demonstrated good internal consistency (Cronbach's alpha = .75). The total score from this scale was used as a measure of children's ability to carry out everyday tasks requiring a long-term memory representation of the correct order of sequences. Five parents did not complete the questionnaire, so no score could be computed on this measure for their children.

Order Working Memory (WM) task. This task measured children's ability to retain serial order information. The English version was modelled on a task developed by Majerus and colleagues (Attout & Majerus, 2015; Attout, Noël & Majerus, 2014; Majerus, Poncelet, Greffe & Van der Linden, 2006). This task measures children's ability to retain and manipulate serial order information by measuring their ability to recreate the correct sequence of a list of animal names that were presented to them through a set of earphones, using cards depicting the animals. The stimuli used were seven monosyllabic English animal words (bear, bird, cat, dog, fish, horse, and sheep). The mean lexical frequencies of these words were established using SUBTLEX-UK word frequencies (SUBTLEX-UK: Van

Heuven, Mandera, Keuleers & Brysbaert, 2014). SUBTLEX-UK presents word frequencies as Zipf values, with values between 1 and 3 representing low frequency words and values between 4 and 7 representing high frequency words. The stimuli demonstrated high lexical frequency according to these values (mean lexical frequency = 4.94, range = 4.67-5.19). The stimuli were used to create 24 word lists, which ranged in length from two to seven words, with four trials per list length. Each word only appeared once per list and the same 24 lists were presented to all participants. The stimuli were recorded by a female voice; an inter-stimulus interval of 650 ms was used. Mean item duration was 565 ms (range = 407-674 ms). For each correctly recalled sequence, children were given a score of 1. Split-half reliability estimates, using the Spearman-Brown formula, indicated good reliability (T1; $r = .93$. T2; $r = .95$).

Daily events task. A modified version of Friedman's (1990) temporal ordering task was used to measure children's ability to judge the correctness of the order of familiar daily events. Children were first trained on how to order events using two training sequences (four cards showing a boy playing on a slide, and six cards depicting a sequence in which a boy picked up and opened a present). Children had to correctly order both sequences four times, before they could proceed to the next phase of the training, which involved the items of the experimental sequence. The experimental sequence consisted of six cards that represented six familiar events that happen during the day (waking up, getting dressed, going to school, eating lunch, eating dinner and going to bed). For the training phase, children were first told what each picture represented and were shown the correct order by the experimenter. Then the cards were shuffled and children were asked to recreate the correct order. For the experimental sequence, children learned the names for each of the daily events and saw the correct order in which these events should go. After this, children were given a computer-based task in which they were told that they would see any three of the daily events and that their task was to judge whether the order was correct or not, from right to left, by pressing a tick or a cross on the touchscreen monitor. Half of the 24 trials (there were 12 sets that were presented twice) showed a triad of events in the correct order, the other half showed a triad that was in the incorrect order. Children were given a score of 1 for each correct answer and a measure of children's reaction times, for correct trials only, was also taken. Since each trial was presented twice, a split-half reliability was calculated using the Spearman-Brown coefficient, which was found to be adequate (T1; *r* = .57. T2; *r* = 76.). Due to the relatively high error rate, reliability for RTs for correct trials was not computed, and the RT measure was not considered further.

Number ordering*[2]*. This task assessed children's early knowledge of the order of symbolic numbers. At T1, children were shown the correct sequence of the numbers 1-9 using cards. These cards were then shuffled

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[2] The typical task in the literature that is used to measure number ordering ability is a computer-based task in which children are shown dyads or triads of numbers and have to judge whether the order is correct or incorrect/ascending or descending. I piloted a computer-based number ordering task with children from this age group using triads (i.e., comparable to our daily events ordering task) and found that they struggled to perform the task, even after a short training that was provided using cards representing the numbers. By contrast, they were able to complete the computer-based version of the Daily events task, after a training session with cards representing the events.

and children were asked to recreate the correct forward order (involving two trials). This procedure was then repeated for the backward sequence of numbers (two trials). In two subtasks, children also ordered the numbers forwards (4 trials) and backwards (4 trials) from different starting positions, with a score of 1 given for each correct trial. The proportion of correct responses was calculated based on performance on all 4 of the ordering tasks. A reliability estimate for the total score was high (Cronbach's alpha = .93).The number ordering task used at T2 was a computerised task which was based on the same task used by Lyons and Ansari (2015). After a fixation cross appeared on the screen for 1000ms, children were shown a triad of single-digit numbers from 1-9 (each number was displayed in size 200 Arial font) on the screen and they had to indicate whether the numbers were in the correct ascending order or not, by pressing one of two buttons on the screen. The triad was displayed on the screen until the participant made a response. The numerical distance was manipulated in this task (referring to the numerical distance between the first and last numbers in correctly-ordered trials, and between the first and second number in incorrectly-ordered trials), as was whether the triad was in the correct or incorrect order (half of the trials were in the correct order, half were in the incorrect order). There were 48 trials in the task, with 8 trials per numerical distance (the distance ranged from 2-7 numbers). Children's overall mean accuracy was the measure of performance on this task. A reliability estimate for mean accuracy was high (Cronbach's alpha = .94), as was the reliability estimate for reaction time (Cronbach's alpha = .84).

Counting. This task was based on the number sequence elaboration task, as outlined in Hannula and Lehtinen (2005). In the first part, children were asked to count from 1 until the highest number they could think of (they were stopped if they reached 50) in two trials. In two further subtasks, children also counted forwards and backwards from different starting points. Children could correct themselves once during any trial. The reliability estimate for both forward and backward subtasks combined was good (T1; Cronbach's Alpha = .77. T2; Cronbach's Alpha = .75). Given the strong correlation between counting until the highest number and both forward (r (88) = .76, $p < .001$) and backward counting (r (88) = .65, $p < .001$), a total counting score was calculated by adding z-scores for all 3 counting measures.

3.2.2.2 Magnitude-processing measures and maths achievement

Non-symbolic Addition[3]. This task measured the ability to represent and manipulate non-symbolic quantities and was based on the procedure

[3] This task was selected instead of non-symbolic comparison, due to the inconsistency of the evidence supporting a link between non-symbolic comparison and maths in developmental studies (De Smedt, Noël, Gilmore & Ansari, 2013), which may be, in part, due to a lack of an agreed measurement of task performance used in these studies (e.g., Inglis & Gilmore, 2014; Price, Palmer, Battista & Ansari, 2012). In contrast, the non-symbolic addition task has been found to be a longitudinal predictor of maths achievement, as well as being related to mastery of both number words and symbols, which underlies much of early maths learning (Gilmore, McCarthy & Spelke, 2010). Furthermore, other evidence (Gilmore, Attridge, De Smedt & Inglis, 2014; Iuculano, Tang, Hall & Butterworth, 2008) has showed that performance on non-symbolic addition and comparison tasks are correlated, suggesting that both tasks are measuring the same underlying construct, (e.g., Sasanguie, Defever, Maertens & Reynvoet, 2014).

used by Gilmore, McCarthy and Spelke (2010), in which children view two sets of blue dots or 'marbles' that a character had, which appear one after the other on the left-hand side of the screen, and have to estimate the sum of the two arrays (sum array) and compare that sum to the quantity of a third array (comparison array, composed of red dots) that a different character had, which appeared on the right-hand side of the screen. The numerical ratio of the sum and comparison arrays was manipulated across the 24 trials (1:2, 3:5, and 2:3), with 8 trials per ratio. The number of dots for both arrays varied from 6 to 45; 6 being the lowest number of dots as this reduced the possibility that children could subitize the number of dots presented. Perceptual variables (dot size, density and array size) were also varied, so that they correlated with numerosity on half the trials (congruent trials) and were uncorrelated on the other half of the trials (incongruent trials), reducing the possibility that children may have used perceptual information as a cue when judging which array was the most numerous. Furthermore, the trials were designed in a way so that it was not possible for the children to perform above chance if they simply responded on the basis of a comparison between the number of blue dots in the second set and the number of red dots. In each trial the number of red dots was at least 1.5 times greater than the number of blue dots in the second set. Nevertheless, the overall number of blue dots was larger in half of the trials than the overall number of red dots, whereas in the other half of trials the opposite was true. In the task, children had to press one of two buttons on the touchscreen to indicate which character they thought had the most marbles. They completed four practice trials, with feedback given on their performance, followed by 24 experimental trials. Children were given a score of 1 if they correctly judged which character had the most marbles. Reliability for this task for accuracy was quite low, but acceptable (T1; Cronbach's alpha = .50. T2; Cronbach's alpha = .63). However, one-sample *t*-tests confirmed that children performed above chance at each ratio. As with the Daily events task, due to the relatively high error rate, reliability for RTs for correct trials was not computed, and the RT measure was not considered further.

Number Comparison. Children's ability to compare symbolic quantities was assessed using a computer-based Number Comparison task (e.g., Dehaene, Dupoux, & Mehler, 1990) in which children were presented with a target number (between 1-4 or 6-9) and were asked to press one of two buttons to indicate whether they thought that the number on the screen was bigger or smaller than 5. Each number was presented five times, in a random order, giving a total of 40 experimental trials. These were preceded by 4 practice trials. Children were scored 1 for each trial in which they correctly judged whether the target number was bigger or smaller than 5, with reaction time data also obtained. Reliability estimates for accuracy (T1; Cronbach's Alpha = .88. T2; Cronbach's Alpha = .84) and reaction times (T1; Cronbach's Alpha = .66. T2; Cronbach's Alpha = .91) were good.

***Number Line task*.** The number line task (Cohen & Blanc-Goldhammer, 2011; Laski & Siegler, 2007, Link, Huber, Nuerk & Moeller, 2014; Siegler & Opfer, 2003) was used to assess children's ability to spatially represent numbers along a mental number line. This task used the number-to-position version, in which children used their finger to indicate the position on the number line where a target number should go. This version used 1-10 and 1-20 scales, and it was framed as a game in which the children had to help Postman Pat to deliver presents to houses on different streets (Aagten-Murphy et al., 2015). There were six experimental trials, in which the child was asked to indicate the position of numbers 3, 4, 6, 7, 8 and 9. For the 1-10 number line, the numbers 5 and 10 were used as the two practice trials; for the 1-20 number line, the numbers 10 and 20 were used as the two practice trials, whilst the child was asked to indicate the position of the numbers 4, 6, 8, 13, 15 and 18 in the six experimental trials, which were presented in a random order. Children's error for each individual trial was calculated as the distance in pixels between children's estimated position and the actual position of the target number. The average of children's errors across both 1-10 and 1-20 scales was used as the overall measure of estimation error for the task. A reliability estimate was computed (T1; Cronbach's Alpha = .70. T2; Cronbach's Alpha = .71).

Maths Achievement. At the end of their first year of school, children's maths ability was assessed by administering a 28-item maths achievement test, consisting of questions from the calculation subtest of the Woodcock-Johnson III tests of achievement (Woodcock, McGrew & Mather, 2001) and from Form A of the Test of Early Mathematics Ability (TEMA-3; Ginsburg & Baroody, 2003). The questions from the calculation subtest contained 6 addition and 4 subtraction problems, whilst the questions from the TEMA-3 included the counting of objects and animals, selecting the next number after a given number in the counting list, as well as selecting which number is larger from a choice of two. At the end of their second year of school, children were assessed using the age-appropriate version of the Maths Assessment for Learning and Teaching (MALT; Williams, 2005) which consisted of 30 questions, assessing counting and understanding number (9 questions), knowing and using number facts (7 questions), calculating (8 questions) and measuring (6 questions). Children's raw scores on both maths measures were used in the analyses. The reliability estimates for the maths measure at the end of children's first year of school (Cronbach's alpha = .91) and for the MALT at the end of children's second year (Cronbach's alpha = .83) were high.

3.2.3 Procedure

The study received ethical approval from the Human Ethics Committee of the School of Psychology, Queen's University Belfast. In year 1, all children completed the Number Ordering task, followed by the Number Comparison task, the Animal Race task and finally, the Non-Symbolic Addition task in the first session. Session 1 was carried out from November to March. In Session 2, children completed the Daily Events Order Task, followed by the WPPSI-III subtests, then the Baseline Reaction Time Task, Counting task and then finally, the Number Line task. Session 2 was carried out from March to May. In year 2, the sessions were identical to those in year 1 (except that the number ordering task in year 2 was computerised and the counting task now involved counting to 100, and backwards and forwards from different starting points to those used in year 1). Session 1 was carried out from March to April of the following year;

session 2 was carried out from April to May. The computer-based tasks were designed using E-Prime Version 2.0. These tasks were presented on a touch screen, connected to a laptop. At the end of each school year (Time 1 = end of year 1; Time 2 = end of year 2), children completed the maths achievement test in small groups of 3-6, in which the experimenter read out the questions and instructed the children to write down their answers. All other tasks were administered individually.

3.3 Results

Descriptive statistics for both accuracy and reaction times are included in Table 3.1 for T1 results, Table 3.2 for T2 results and Table 3.3 shows the results of *t*-test and correlation analyses between the measures at both time-points. At T1, the median number that children could count to (out of 50) was 39; at T2, most children could count to 100 (median = 100). At T1, most children performed well on the two counting subtasks (forward and backward counting mean accuracy = 76%) and on Number ordering (82%). Two children performed very poorly in these. At T2, children's performance was reasonable on the number ordering task (accuracy = 76%), given that this task was much more difficult than the measure used at T1. In the non-numerical ordering tasks; children did not perform quite as well. In the Daily events task, children's accuracy was 65% at T1, which was, nevertheless, above chance; t (89) = 11.10, $p < .001$; this increased to 76% accuracy at T2. In the order working memory task at T1, children were able to recall 9.52 sequences in the correct order, which corresponded to an average serial order memory span of 3.62 (SD = 1.50). One year later, children were able to recall 10.89 sequences in the correct order, which corresponded to an average serial order memory span of 3.78 (SD = 1.44). Children's mean score on the OPQ was 44.02 out of 56, with parents tending to rate their children highly in terms of being able to carry out everyday tasks with a strong ordering component. As previously mentioned, children's accuracy on the non-symbolic addition task was relatively low, but their performance on the task was above chance; t (89) = 5.09, p < .001. Their performance on this task at T2 increased to 64%. Children performed much better on the number comparison task (accuracy at T1 = 71%; accuracy at T2 = 95%). In the number line task, children's estimates on the 1-10 scale were on average about 1.8 numbers away from the target number, whilst their estimates on the 1-20 number line were on average about 3.4 numbers from the target; these deviations from the target number improved at T2 to 1.43 and 2.80 for the 1-10 and 1-20 scales respectively.

Table 3.3 shows the correlation coefficient between T1 and T2 task performance for each measure. Vocabulary scores at T1 and T2 were strongly related to each other, whilst Block Design scores were moderately and significantly related to each other. Regarding the correlations between ordinal tasks at both time points, non-numerical ordering task (Order WM and Daily events) performance at T1 and T2 were strongly and significantly correlated (although reaction times for the Daily events task at T1 and T2 were unrelated). The Counting forward and backward subtests were moderately and significantly correlated at both time points. For the magnitude tasks, Non-symbolic addition performance (accuracy and RT) at T1 correlated moderately with their respective measures at T2. The correlation between reaction times in the Non-symbolic addition task remained significant, after controlling for baseline reaction times; r (83) = .32, p = .003. Number comparison accuracy at T1 and T2 was unrelated, but reaction times did correlate moderately, even after controlling for baseline reaction times; r (83) = .28, p = .006. Performance on the Number line task at T1 and T2 was unrelated. Paired *t*-tests revealed that children improved significantly at T2 on all measures that they had also completed at T1, although children did not perform significantly faster at T2 on the non-symbolic addition task.

Table 3.1. Descriptive statistics for all measures at T1.

	T1		
Measure	Min.	Max.	M *(SD)*
Vocabulary (Scaled score)	4	17	8.52 *(2.10)*
Block Design (Scaled score)	4	16	10.12 *(3.15)*
Order Processing Questionnaire	21	56	44.02 *(7.69)*
Order WM	1	16	9.52 *(4.54)*
Daily Events Acc.	.38	1	.65 *(.13)*
Daily events RT (ms)	1310	13538	6142.99 *(2481.35)*
Symbolic number ordering acc.[4]	0	1	.82 *(.30)*
Symbolic number ordering RT (ms)	-	-	-
Counting to 50 (median)	6	50	39 *(13.15)*
Counting to 100 (median)	-	-	-
Counting forward and backward	0	1	.76 *(.22)*
Non-symbolic addition acc.	0.3	.88	.56 *(.11)*
Non-symbolic addition RT (ms)	916	10023	2451.30 *(1268.59)*
Number comparison acc.	.40	1	.71 *(.19)*
Number Comparison RT (ms)	778	6059	2404.04 *(1044.16)*
Number Line (mean scaled error)	64	453	191.52 *(74.90)*
Baseline RT (ms)	860	2284	1435 *(283.71)*
Maths	1	28	23.24 *(4.88)*

$* p < .05$, $** p < .01$

Table 3.2. Descriptive statistics for all measures at T2.

	T2		
Measure	Min.	Max.	M *(SD)*
Vocabulary (Scaled score)	3	16	9.40 *(2.59)*
Block Design (Scaled score)	7	18	11.21 *(2.53)*
Order Processing Questionnaire	-	-	-
Order WM	1	19	10.89 *(4.37)*
Daily Events Acc.	.46	1	.76 *(.13)*
Daily events RT (ms)	381	12890	5486.37 *(1913.63)*
Symbolic number ordering acc.	.38	1	.76 *(.21)*
Symbolic number ordering RT (ms)	499	10558	4295.63 *(1842.77)*
Counting to 50 (median)	-	-	-
Counting to 100 (median)	20	100	100 *(14.28)*
Counting forward and backward	.25	1	.92 *(.16)*
Non-symbolic addition acc.	.33	.96	.64 *(.13)*
Non-symbolic addition RT (ms)	867	7550	2202.77 *(993.21)*
Number comparison acc.	.55	1	.95 *(.08)*
Number Comparison RT (ms)	1154	4132	2041.38 *(649.46)*
Number Line (mean scaled error)	41	325	126.94 *(56.00)*
Baseline RT (ms)	481	1808	1167.35 *(235.52)*
Maths	7	29	21.74 (4.71)

* $p < .05$, ** $p < .01$

Table 3.3. Correlation and *t*-test analysis between task performance at T1 and T2.

Measure	*r*	*t*
Vocabulary (Scaled score)	.61**	10.45**
Block Design (Scaled score)	.41**	12.01**
Order Processing Questionnaire	-	-
Order WM	.62**	3.36**
Daily Events Acc.	.47**	8.10**
Daily events RT (ms)	.20	2.10*
Symbolic number ordering acc.	-	-
Symbolic number ordering RT (ms)	-	-
Counting to 50 (median)	-	-
Counting to 100 (median)	-	-
Counting forward and backward	.35**	6.46**
Non-symbolic addition acc.	.29**	5.66**
Non-symbolic addition RT (ms)	.35**	1.41
Number comparison acc.	.20	11.76**
Number Comparison RT (ms)	.31**	3.28**
Number Line (mean scaled error)	-.01	6.63**
Baseline RT (ms)	.41**	8.98**
Maths	.69**	-

* $p < .05$, ** $p < .01$

3.3.1 Zero-order, partial and bootstrap correlations between the measures at T1 and maths achievement at the end of children's first year of school

Regarding the relationship between the general ability measures and the other tasks used at T1, Table 3.4 shows that Vocabulary scores were significantly positively correlated with order-processing measures (Order WM, Daily events and Counting), Non-symbolic addition and maths scores. Block design scores were significantly and positively correlated with the order-processing measures (Order WM, Daily events, Number ordering), as well as performance on the Number line task. Finally, higher deprivation scores were significantly related to lower performance on both IQ measures and maths, as well as lower performance on the Order WM, Daily events, Number ordering and Number comparison tasks.

As shown in Table 3.4, there were significant correlations between the order-processing measures and maths at the end of children's first year of school; children's maths ability was related to their scores on the OPQ, Number ordering ability, Daily events task accuracy, Counting ability and Order WM performance. Of the magnitude measures, only Number comparison was found to be related to maths. After controlling for age, deprivation scores and verbal and nonverbal intelligence, Number comparison performance was no longer significantly related to maths performance ($p = .741$). OPQ scores; $r(78) = .26, p = .020$; Number ordering performance; $r(78) = .25, p = .024$; Daily events accuracy; $r(78) = .36, p = .001$; Counting ability; $r(78) = .43, p < .001$, and Order WM accuracy; r (78) = .30, p = .008, remained significantly related to maths after controlling for the covariate measures.

A Bootstrap procedure (using 10,000 samples) was also applied to assess the reliability of the relationship between the measures which had previously been observed as having a significant zero-order and/or partial correlation with maths, and maths achievement at each time point. This procedure allowed for a 95% confidence interval to be computed for the correlations between each measure and children's maths ability and if any measure was found to have a significant bootstrap correlation with maths, then it was considered to be robustly related to maths achievement. Figure 3.1 shows 95% bootstrap confidence intervals between the T1 measures and maths achievement at the end of children's first year of school. Figure 3.1 shows that the measures, which had previously shown significant zero-order and/or partial correlations with maths at the end of children's first year of school, also showed significant zero-order bootstrap correlations with maths.

Table 3.4. Zero-order correlations between all measures at T1 and maths achievement at the end of T1 and T2. *Task abbreviation: Q: Questionnaire. WM: Working memory.*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
(1) Age	-													
(2) Vocabulary	.04	-												
(3) Block Design	.09	.09	-											
(4) Deprivation	.11	-.41**	-.22*	-										
(5) Order Processing Q.	.08	.15	.03	-.09	-									
(6) Order WM	.17	.22*	.30**	-.22*	.18	-								
(7) Daily Events	-.09	.38**	.29**	-.27**	-.08	.44**	-							
(8) Number Ordering	.14	.19	.24*	-.23*	.26*	.41**	.24*	-						
(9) Counting	.09	.27**	.13	-.10	.15	.54**	.34**	.36**	-					
(10) Non-Symbolic Addition	-.23*	.24*	.12	-.19	-.14	.11	.22*	.19	.02	-				
(11) Number Comparison	.06	.18	.09	-.22*	.20	.28**	.34**	.29**	.29**	.15	-			
(12) Number Line (Error)	.21*	-.02	-.26*	.10	.11	-.05	-.15	-.05	-.20	-.14	-.04	-		
(13) Maths (Year 1)	-.004	.32**	.16	-.26*	.30**	.32**	.46**	.40**	.54**	.14	.21*	.02	-	
(14) Maths (Year 2)	.10	.37**	.29**	-.29**	.28*	.23*	.41**	.38**	.43**	.30**	.24*	-.17	.69**	-

* $p < .05$, ** $p < .05$

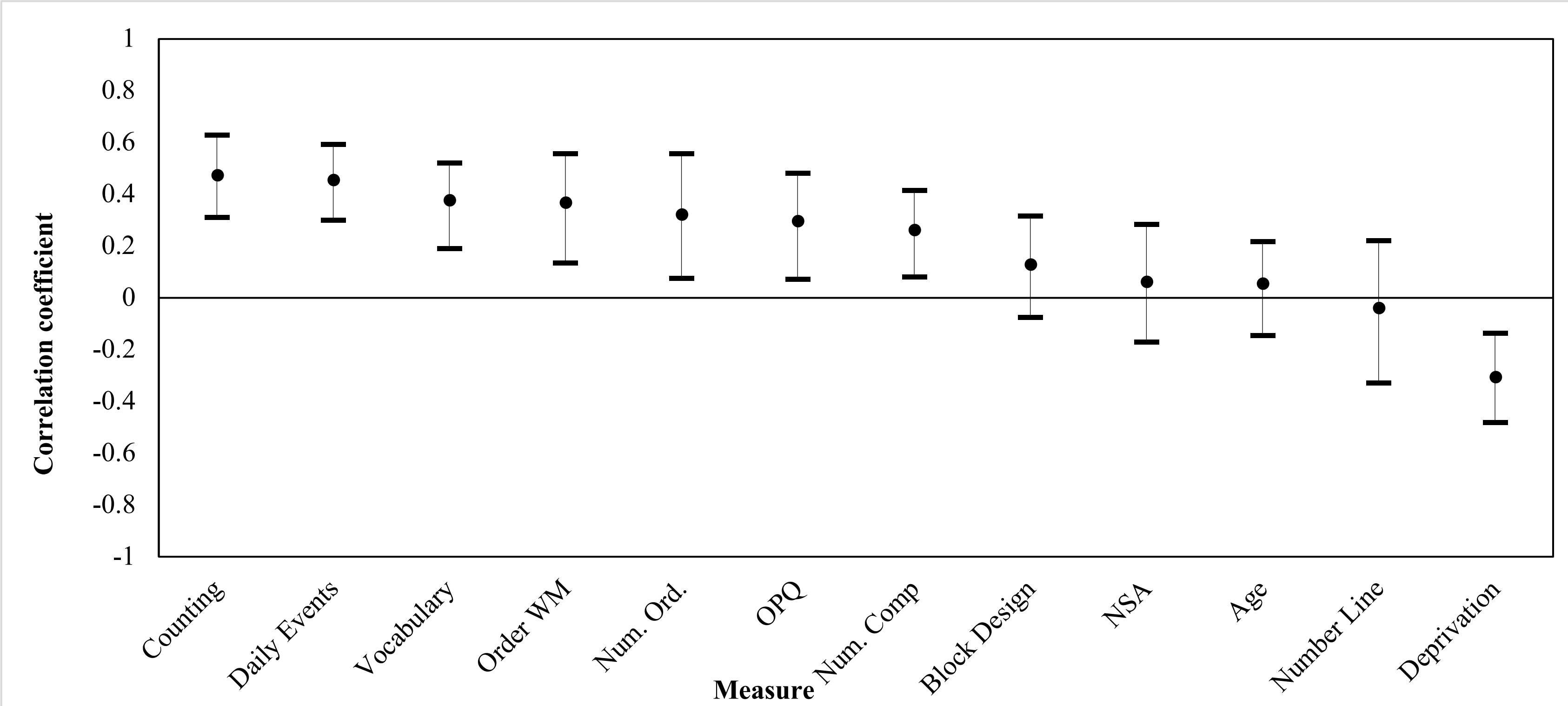

Figure 3.1. Bootstrap correlations between all measures at T1 and maths achievement at T1.

Task Abbreviation: Num: Number. NSA: Non-symbolic addition. OPQ: Order Processing Questionnaire. WM: Working memory

3.3.1.1 T1 Predictors of maths performance

The regression analyses regarding the relationship between the predictor variables and maths performance at each time point followed a similar procedure to that of Szűcs, Devine, Soltész, Nobes and Gabriel (2014). For each regression model, the variables that had a significant bootstrap correlation with maths were entered first. Non-significant predictors of maths in each model were then removed and each predictor, which had a significant correlation with maths (after controlling for the effect of the other variables), but not a significant bootstrap correlation, was entered into the model one by one to examine whether they became significant. Then, the four covariates (age, deprivation scores, vocabulary and block design) were entered into the model, to examine whether they changed significant predictors and improved fit. At each time-point, the model that explained the greatest proportion of variance, with only significant predictors in the model, was selected.

Table 3.5 shows the initial and final models for T1 measures that predicted maths at the end of children's first year of school. The initial model consisted of OPQ scores, Order WM, Daily events, Number ordering, Counting and Number comparison accuracy. This model explained 37% of the variance in maths scores, however, this model contained a number of non-significant predictors of maths (order WM; $\beta = -.07$, *n.s*; number ordering; $\beta = .12$, *n.s*; number comparison; $\beta = -.03$, *n.s*). These measures were removed and only the significant predictors (OPQ scores, Daily events and Counting accuracy) were entered into the next model. When adding them to the model one by one, none of the remaining predictors explained significant additional variance in maths performance. Thus, this was accepted as the final model (see Table 3.5).

Table 3.5. Stepwise regression models (following the procedure outlined by Szűcs et al. (2014)) showing both the initial and final models predicting maths achievement at the end of children's first year of school.

		β	t	p
Initial model	Daily events	.39	3.90	< .001
	Counting	.33	3.09	.003
	Order Processing Questionnaire	.27	2.89	.005
	Number ordering	.12	1.25	.214
	Order WM	-.07	.65	.520
	Number comparison	-.03	.31	.759
Final model	Daily events	.38	4.17	< .001
	Counting	.32	3.49	.001
	Order Processing Questionnaire	.28	3.23	.002

Initial model: $R^2 = .37$, $F(6, 84) = 9.33$, $p < .001$.

Final model: $R^2 = .39$, $F(3, 84) = 18.39$, $p < .001$

3.3.2 Zero-order, partial and bootstrap correlations between the measures at T1 and maths achievement at the end of children's second year of school

Table 3.2 shows that vocabulary; block design and deprivation scores at T1 were significantly related to maths at T2. Children's T1 OPQ scores, Daily events task accuracy, Number ordering ability, Order WM accuracy, Daily events accuracy and Counting ability were related to maths ability at the end of children's second year of school. For the magnitude measures, both Non-symbolic addition accuracy and Number comparison accuracy were related to maths. After controlling for age, deprivation scores and verbal and non-verbal intelligence, the only significant relationships with maths were observed for OPQ scores, r (75) = .24, p = .033; Counting ability, r (75) = .24, p = .033; and Number ordering performance, r (75) = .24, p = .035.

Figure 3.2 shows 95% bootstrap confidence intervals between T1 measures and maths achievement at the end of children's second year of school, whilst Figure 3.3 shows 95% bootstrap confidence intervals between T2 measures and maths achievement at the end of children's second year of school. Figure 3.2 shows that Order WM accuracy [r = .17, 95% CI (-.11, .41)] was the only measure that was not robustly related to maths at the longitudinal level, of all the measures that had previously been related to maths at the end of children's second year of school[4].

[4] Zero-order correlations between the robust correlates of maths at each time point and the different components of the maths assessment are presented in Appendices C-E. Typically, the best predictors of maths at each time point were significantly related to all aspects of maths.

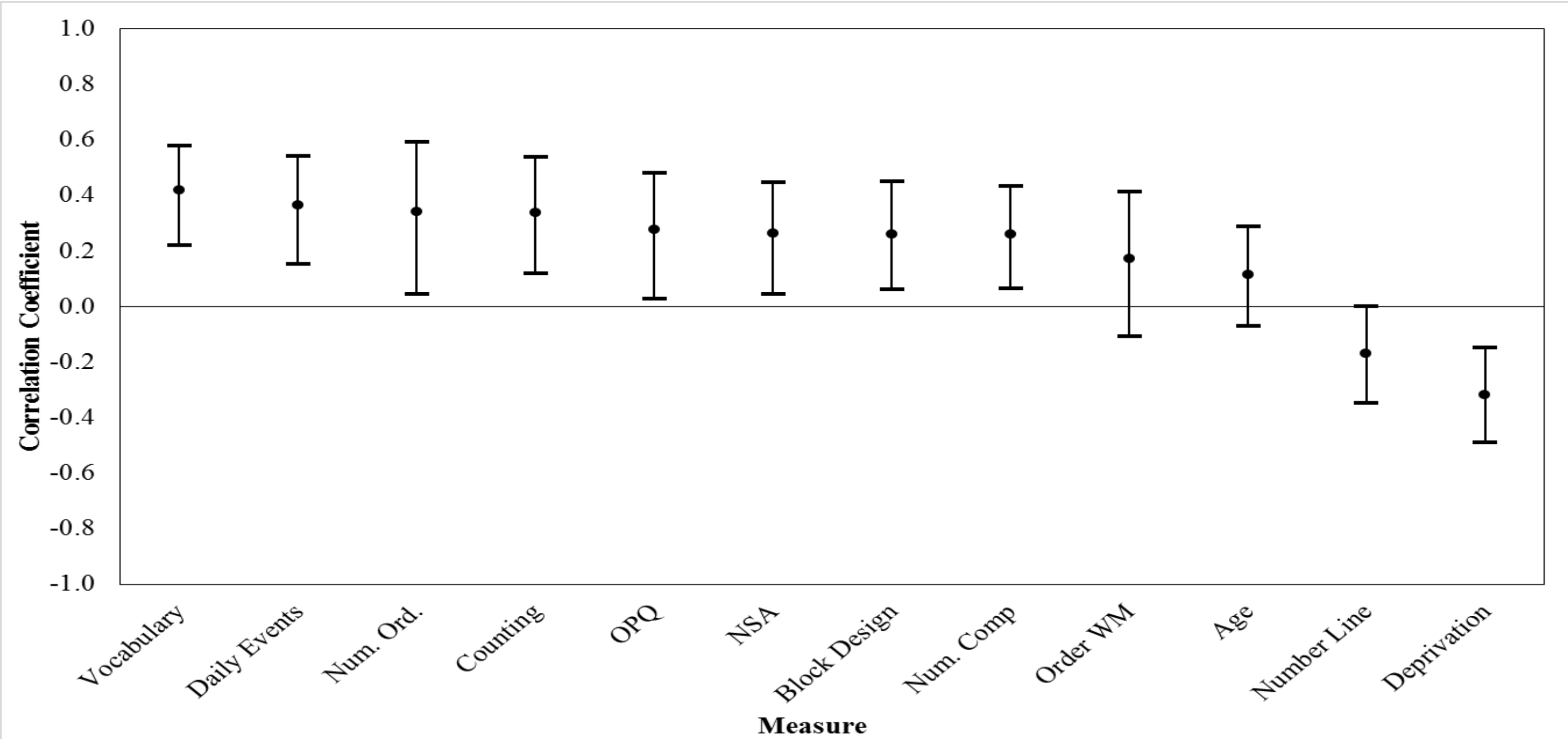

Figure 3.2. Bootstrap correlations between all measures at T1 and maths achievement at T2.

Task Abbreviation: Num: Number NSA: Non-symbolic addition. OPQ: Order Processing Questionnaire. WM: Working memory

3.3.2.1 T1 predictors of maths skills at the end of the second school year

A regression analysis was conducted, with children's maths scores at the end of their second year of school as the criterion, and the T1 measures which had previously correlated with maths as the predictors. Table 3.6 shows the initial and final models for the T1 measures that significantly predicted maths at the end of children's second year of school. The initial model consisted of OPQ scores, Daily events, Number ordering, Counting, Non-symbolic addition and Number comparison accuracy. This initial model explained 30% of the variance in children's maths scores at the end of their second year of school. The non-significant predictors (Number ordering, Counting and Number comparison) were removed and the next model contained OPQ scores, Daily events and Non-symbolic addition accuracy, which explained 27% of the variance in maths performance. The two intelligence measures and deprivation scores did not explain significant additional variance in maths performance, although age was a significant factor when included in the model containing OPQ scores, Daily events and Non-symbolic addition accuracy, with this model explaining 30% of the variance in children's maths performance at the end of their second year of school[5].

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[5] Additional regression analyses were performed to investigate whether the results of the cross-sectional and longitudinal regression models were the same for predicting only the arithmetic/calculation measures at T1 and T2. These analyses were conducted to demonstrate that ordering abilities were not simply related to a composite measure of maths achievement (which included various basic components of early maths ability, including some that were closely related to ordering). The same three predictors (OPQ, daily events and counting) that significantly predicted maths achievement at T1

As a final step, we also checked if the longitudinal predictors of formal maths skills at the end of the second year of school also remained significant if the effect of formal maths skills at the end of the first school year were taken into account. We did this by adding formal maths skills at T1 as a predictor to the final regression model presented in Table 3.6. This analysis addressed the question of whether these longitudinal predictors of maths also predicted growth in maths skills during the second year of school. The model is presented in Table 3.7. This model explained 41% of the variance in T2 formal maths skills with formal maths skills at T1, the OPQ and Non-symbolic addition as significant predictors. The effect of the Daily event ordering task was no longer significant, and the effect of age was also reduced to a non-significant trend.

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also predicted arithmetic scores at T1 (these 3 predictors accounted for 31% of the variance in arithmetic scores). Three of the four significant longitudinal predictors of maths at T2 (OPQ, Non-symbolic addition and Daily events) also significantly predicted calculation scores at T2 (accounting for 19% of the variance in calculation scores). Age was not found to be a significant longitudinal predictor of calculation abilities. (Detailed results of these analyses can be found in Appendices F and G).

Table 3.6. Stepwise regression models (following the procedure outlined by Szűcs et al. (2014)) showing both the initial and final regression models longitudinally predicting maths achievement at the end of children's second year of school.

		β	*t*	*p*
Initial				
Model	Order Processing Questionnaire	.28	2.77	.007
	Non-Symbolic addition	.26	2.60	.011
	Daily events	.25	2.38	.020
	Counting	.19	1.80	.075
	Number ordering	.11	1.07	.289
	Number Comparison	.04	.35	.728
Final	Daily events	.35	3.67	< .001
Model	Order Processing Questionnaire	.32	3.36	.001
	Non-symbolic addition	.30	3.04	.003
	Age	.20	2.06	.042

Initial model: $R^2 = .30$, $F(6, 81) = 6.71$, $p < .001$.

Final model: $R^2 = .30$, $F(4, 81) = 9.53$, $p < .001$.

Table 3.7. Stepwise regression model predicting formal maths achievement at the end of children's second year of school, taking into account the effect of formal maths achievement at the end of the first school year.

	β	t	p
T1 maths	.41	3.92	<.001
Daily events	.16	1.62	.109
Order Processing Questionnaire	.19	2.03	.045
Non-symbolic addition	.26	2.93	.004
Age	.17	1.95	.054

$R^2 = .41$, $F(5, 81) = 12.13$, $p < .001$.

3.3.3 Zero-order, partial and bootstrap correlations between the measures at T2 and maths achievement at the end of children's second year of school

As shown in Table 3.8, all measures (with the exception of age and Number line estimation) were significantly correlated with maths at T2. After controlling for age, deprivation scores and verbal and non-verbal intelligence, the only significant relationships with maths were observed for Counting ability, r (75) = .45, $p < .001$; Non-symbolic addition, r (75) = .35, $p = .002$; and Number comparison performance, r (75) = .27, $p = .018$.

As shown in the bootstrap correlation analysis in Figure 3.3, there were three T2 measures that did not show a significant bootstrap correlation with maths at T2, of all the measures that had previously been related to maths at the end of children's second year of school; Order WM accuracy

[r = .20, 95% CI (-.10, .46)]; Daily events accuracy [r = .21, 95% CI (-.03, .41)] and Number comparison accuracy [r = .36, 95% CI (-.02, .61).

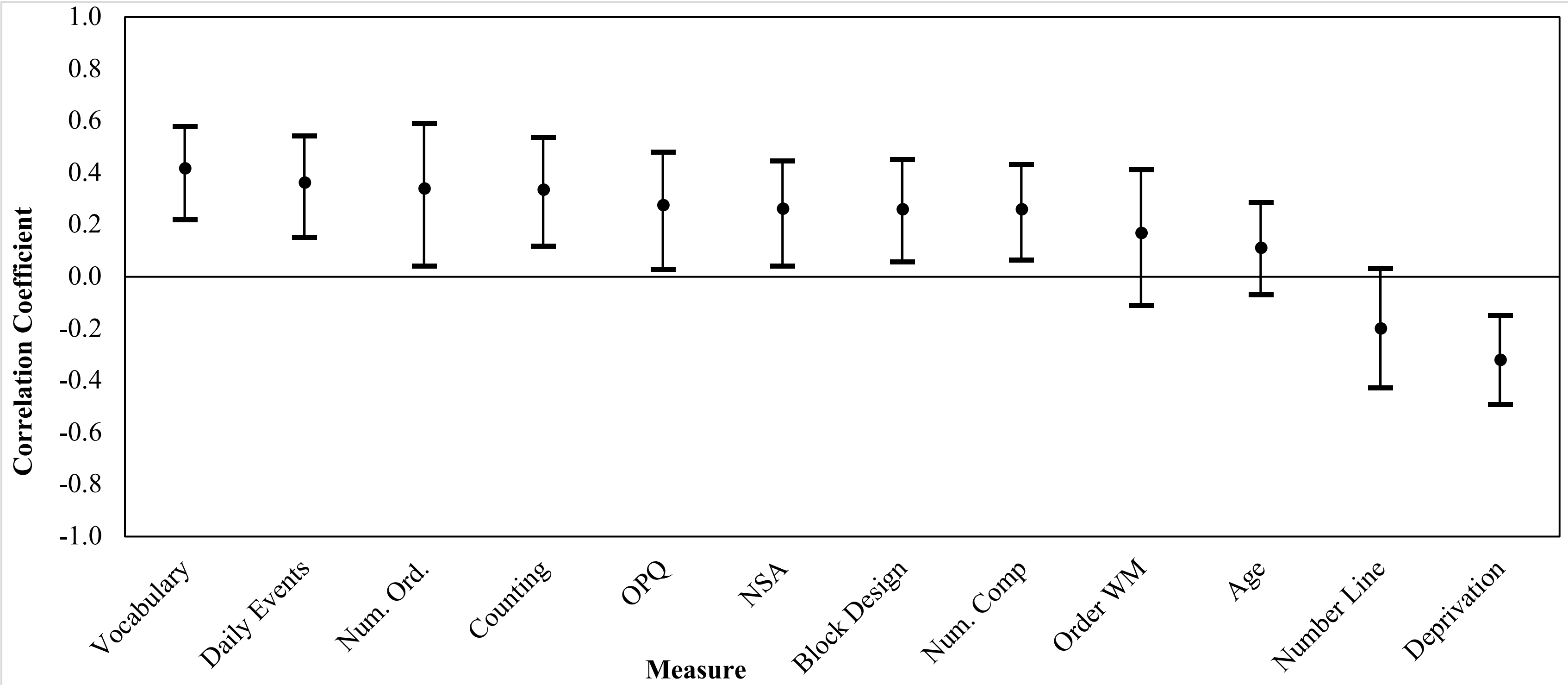

Figure 3.3. Bootstrap correlations between all measures at T2 and maths achievement at T2. *Task Abbreviation: Num: Number NSA: Non-symbolic addition. OPQ: Order Processing Questionnaire. WM: Working memory.*

Table 3.8. Zero-order correlations between all measures at T2 and maths at T2. Task Abbreviation: Add.: addition. Q: Questionnaire. WM: Working memory.

* *p < .05,* ** *p < .01*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
(1) Age	-											
(2) Vocabulary	.04	-										
(3) Block Design	.20	.33**	-									
(4) Deprivation	.02	-.32**	-.34**	-								
(5) Order WM	.19	.30**	.29**	-.20	-							
(6) Daily Events	-.09	.35**	.31**	-.30**	.15	-						
(7) Number ordering	.02	.56**	.30**	-.25*	.45**	.33**	-					
(8) Counting	-.02	.27*	.26*	-.19	.37**	.25*	.41**	-				
(9) Non-Symbolic Addition	.20	.26*	.22*	-.21	.25*	.11	.36**	.22*	-			
(10) Number Comparison	.07	.32**	.16	-.19	.37**	.36**	.45**	.38**	.19	-		
(11) Number Line (Error)	.14	.10	.04	.09	.03	-.07	-.04	-.15	.05	.01	-	
(12) Maths (Year 2)	.20	.35**	.26*	-.29**	.28**	.25*	.37**	.54**	.43**	.52**	-.09	-

3.3.3.1 T2 predictors of maths

A regression analysis was conducted, with children's maths scores at the end of their second year of school as the criterion, and the T2 measures which had previously correlated with maths as the predictors. Table 3.9 shows both the initial and final models for T2 measures that predicted maths achievement at the end of children's second year of school. This initial model explained 37% of the variance in children's maths scores at the end of their second year of school. The non-significant predictor (Number ordering) was removed and the next model contained OPQ scores, Counting and Non-symbolic addition accuracy, which explained 38% of the variance in maths performance. When adding the other predictors to the model one by one (Order WM and Daily events accuracy), none of these predictors explained significant additional variance in maths performance. However, when number comparison accuracy was added, it became a significant predictor, whilst the OPQ became a non-significant predictor and was thus removed from the model. The next model contained three significant predictors (Counting, Non-symbolic addition and Number comparison accuracy) and accounted for 48% of the variance in children's maths achievement at the end of their second year of school. The two intelligence measures, age and deprivation scores did not explain significant additional variance in maths performance, meaning that the previous tripartite model was accepted as the best-fitting model for predicting maths at T2.

Table 3.9. Stepwise regression models (following the procedure outlined by Szűcs et al. (2014)) showing both the initial and final models concurrently predicting maths achievement at the end of children's second year of school.

		β	t	p
Initial model	Counting	.35	3.29	.002
	Non-symbolic addition	.34	3.62	.001
	Order Processing Questionnaire	.20	2.18	.033
	Number ordering	.04	.36	.717
Final model	Counting	.35	4.09	< .001
	Number comparison	.34	3.96	< .001
	Non-symbolic addition	.30	3.72	< .001

Initial model: $R^2 = .37$, $F(4, 81) = 12.79$, $p < .001$.

Final model: $R^2 = .48$, $F(3, 86) = 27.08$, $p < .001$.

3.4 Discussion

The aim of the current study was to investigate the role of order-processing skills in the development of children's maths abilities during their first two years of formal schooling in Northern Ireland, between the ages of 4 and 6; a younger school-starting age than many other studies which have studied how ordinality is related to early maths achievement. Performance on the Daily events task was the strongest concurrent predictor of children's maths achievement at the end of their first year of primary school, followed by Counting ability and by scores on the Order-Processing Questionnaire. Performance on the Daily events task was also the strongest longitudinal predictor of children's maths achievement at the end of their second year of primary school, followed by scores on the Order-Processing Questionnaire, performance on the Non-symbolic addition task and age. Counting ability was the strongest concurrent predictor of children's maths achievement at the end of their second year of primary school, followed by Number comparison and Non-symbolic addition performance. These findings show the importance of non-numerical ordering abilities in the development of mathematical abilities amongst children who have just began formal education, whilst the importance of symbolic and non-symbolic magnitude-processing skills does not appear to be such an important factor in early numerical development, but rather emerges in terms of its importance to numerical development during children's second year of school.

3.4.1 Order-processing skills play an important role in early numerical development, whilst the importance of magnitude does not emerge until 1 year later

In children's first year of primary school, their performance on numerical and non-numerical order-processing measures was significantly and robustly correlated with their maths achievement at the end of the year, showing the importance of these skills in early numerical development. Children's performance on the Number comparison task was robustly related to maths. However, performance on the Non-symbolic addition task did not correlate with maths achievement, which is in contrast with accounts that suggest the ANS plays an important role in early numerical development (e.g. Chen & Li, 2014).

The regression analysis revealed that children's ability to process non-numerical order for familiar sequences (as measured by the Daily events task and the OPQ) were the strongest predictors of maths at the end of their first year of primary school, and explained variance in maths achievement even after controlling for Counting skills. These results suggest that at the beginning of formal schooling (between the ages of 4 and 5) non-numerical order-processing skills may support the development of symbolic mathematical abilities amongst children who have only began to learn the number system. These results are novel in that they are the first to show the importance of these types of ordering skills to the development of numerical abilities in very young children. The finding that non-symbolic magnitude skills did not even correlate with maths achievement at this stage suggests that the ANS does not play as important a role in early maths learning as previously thought.

All of the magnitude (except Number line estimation) and ordinal measures at T2 correlated with children's maths achievement at the end of their second year of primary school. This shows that after children have engaged in a year of formal schooling, non-symbolic magnitude skills are now also shown to play some role in numerical development. The regression analysis revealed that children's maths performance at T2 was significantly predicted by three numerical-related measures; Counting, Number comparison and Non-symbolic addition. This suggests that magnitude-processing skills, together with Counting skills, explain variance in children's maths scores, at a point in which have already had some experience of formal maths learning, which again suggests that the ANS does not play as strong a role in early numerical development as previously thought, but in fact it may be the case that it only emerges in its importance as a result of maths learning, rather than vice-versa (see Chen & Li, 2014).

These results are similar to those of Sasanguie and Vos (2018), in that these authors found that Number comparison ability mediated the relationship between Number ordering and maths achievement in a sample of children in grade 1 (aged between 5-6), suggesting that children solved mathematical problems in the beginning of school using a strategy based on the comparison of the numerosity of numbers within the symbolic number system. The children in Sasanguie and Vos' study were the same age as the children in the current study were at T2, in which it was found that maths achievement was significantly predicted by magnitude-processing skills, suggesting that magnitude-based strategies may play an important role in solving mathematical problems at this particular stage of development.

Importantly, the results also show that ordinality was a stronger early concurrent (and longitudinal) predictor of maths than magnitude. This conclusion is reached, given that; a) Number comparison was robustly related to maths at T1 and longitudinally related to maths at T2, but was not a significant predictor, and b) non-numerical ordering measures were stronger longitudinal predictors of maths than Non-symbolic addition, a numerical-based task which other studies have demonstrated is related to arithmetical learning (e.g. Gilmore, McCarthy & Spelke, 2010). Both symbolic and non-symbolic magnitude were significant predictors of maths at the end of children's second year of primary school, although the measures were still weaker predictors of maths than counting skills. These results suggest that there is a shift in terms of the importance of certain skills to early maths development. Whilst non-numerical ordering skills may be important in facilitating early numerical development at the beginning of primary school, magnitude-based strategies may be involved in maths performance after children have had some experience of (and perhaps as a result of) formal maths learning.

Although a robust relationship between Number comparison performance and maths skills both at the cross-sectional and longitudinal levels was found, which is also in line with several other studies that showed a strong relationship between number comparison and maths skills at the start of formal education (e.g., Attout et al., 2014; Holloway & Ansari, 2009; Mundy & Gilmore, 2009; Rousselle & Noël, 2007), given the well-established link between this task and maths ability, and the fact that it involves symbolic number processing, it is striking, though, that number comparison did not explain additional variance in maths skills, once the effect of counting skills and everyday ordering abilities were controlled.

3.4.2 Order-processing and magnitude skills longitudinally explained variance in children's maths scores at the end of their second year of school

The results of the current study support the hypothesis that non-numerical order-processing skills are longitudinally predictive of maths. All the ordinal and magnitude measures (except for number line performance) were longitudinally correlated with maths, showing that they were important to numerical development during the Foundation years of primary school. The longitudinal regression analysis (i.e., predicting maths performance at the end of the second school year) showed that non-numerical ordering measures (OPQ scores and Daily events task accuracy) significantly predicted variance in maths achievement more than 1 year later, even when the significant effects of Counting ability, and Non-symbolic magnitude skills were controlled. When the effect of T1 formal maths skills was controlled, only the OPQ and the non-symbolic addition task explained additional variance in T2 formal maths skills, whereas the effect of the Daily events task was no longer significant. This suggests that whilst everyday ordering abilities predicted growth in young children's mathematical ability over a 1 year period, this was not also the case for children's ability to process order for familiar events. Nonetheless, the importance of these measures in early numerical development suggests that it is these skills which may be useful in forming the basis for diagnostic tools aimed at identifying children who may potentially be at risk of developing mathematical difficulties, as well as forming the basis for an early intervention aimed at remediating poor maths skills.

Regarding number line performance, several studies found a reliable relationship between this task and maths achievement in children from as young as 3 years old (e.g., Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Booth & Siegler; 2006, 2008; Link et al., 2014; Siegler & Booth, 2004). In the current study, number line performance did not correlate with maths at the concurrent or longitudinal level, which may be due to methodological issues surrounding the version of the task used in the current study (see Chapter 5 for further discussion).

3.4.3 Number ordering did not predict maths achievement in the early years

Regarding the case of whether the importance of ordinality in maths development is number-specific, the results discussed earlier suggest that this is not the case. An interesting finding was that although Number ordering performance was found to be important to numerical development at both time-points, it did not explain additional variance in maths achievement, over and above the variance explained by the non-numerical ordering tasks at T1, or the magnitude tasks at T2. This is consistent with other work which shows that numerical ordering skills may not be predictive of maths achievement until children are around six (e.g. Attout et al., 2014; Lyons et al., 2014; Sasanguie & Vos, 2018). Based on this, it would be reasonable to expect that for the older children tested in Study 2, Number ordering skills would be more strongly related to maths achievement for children aged 8-11. On the other hand, Counting skills appeared to be more important to early numerical development, suggesting that the extent to which children can verbally reconstruct the correct order of the number system, rather than their ability to mentally process and to provide an answer as to the correctness of the order of a triad of numbers, plays a more important role in their early numerical development.

Nonetheless, these results suggest that children's early general ordering skills may be important to the later development of mathematical abilities at the end of their second year of primary school, and also extend previous findings by showing that, even at the very earliest stages of formal schooling, children's ability to process non-numerical order, as demonstrated in familiar everyday tasks and to a lesser extent, their ability to order daily events, plays an important role in the successful development of more mature maths skills. This extends work with adults (Morsanyi et al., 2017; Sasanguie et al., 2017; Vos et al., 2017) that showed strong relationships between non-numerical ordering tasks and mathematics abilities. Our detailed analyses of the components of the formal maths tests (see Appendices C-E) also showed that ordinality was important to all aspects of maths, including counting, calculation, and the understanding of number facts and measures.

3.4.4 The development of children's performance on non-numerical and maths-related measures between T1 and T2 shows that early maths abilities rely on non-mathematical skills, whilst mathematical-related skills are still developing

Both the correlations between task performance at T1 and T2, as well as the *t*-tests investigating the developmental trajectory of task performance between T1 and T2, provide further insight into the skills which are important to the development of mathematical abilities in the early years of formal schooling.

For magnitude-processing tasks, the correlational analysis between task performance at T1 and T2 revealed a weak, significant relationship between non-symbolic addition performance at T1 and T2, whilst there was no significant relationship between number comparison performance at T1 and T2. Nonetheless, performance on both magnitude tasks improved significantly from T1 to T2. These results suggest that these mathematical-related measures are not necessarily stable during the early years of school, during which time these skills are rapidly developing and they may do so quite rapidly, as children are introduced to formal maths learning. Another interesting point is that the reliability of the Non-symbolic addition was very low at both time points, whereas the Number comparison task had good reliability at both T1 and T2; this suggests that the low correlations was not purely the result of poor reliability, given that performance on the latter was quite reliable but the correlations between both time points was non-significant.

In contrast, the ordinal tasks show a different pattern of results. Children performed significantly better on all ordinal measures at T2, compared to T1 (except for daily events reaction times). Performance at both time points, for both Order WM and Daily events tasks, were moderate-to-strongly and significantly correlated with each other. Furthermore, these tasks showed good reliability (except for daily events at T1, due to the number of errors children made on this task). This suggests that non-numerical ordering skills could be considered as good candidate skills upon which early mathematical knowledge may be built upon, because they are already established at the beginning of formal education.

Together, these results suggest that there is a fundamental shift in the problem-solving strategies of children, at the beginning of primary school, as a consequence of their interaction with formal education. The results appear to show that initially, children's maths skills rely on basic, non-numerical skills. At the same time, children's ability to utilize basic maths-related skills are rapidly developing at this early stage. These findings provide support for the conclusions drawn from the regression analyses; that initial formal maths learning relies on non-numerical ordering abilities, whilst magnitude-processing skills do not develop until children are slightly older and have had some experience within the schooling system.

3.4.5 Correlations show that performance on numerical and non-numerical ordering tasks are related, and performance on both are (somewhat) related to magnitude measures

The correlation analysis showed that at both T1 and T2, numerical and non-numerical measures were significantly correlated with each other. At T1, scores on the OPQ were related to performance on the Number ordering task; Order WM performance correlated with both Number ordering and Counting ability, whilst Daily events accuracy was significantly related to Counting ability and Number ordering performance. At T2, the relationship between Order WM scores and Number ordering (the latter being measured by a computer-based task at T2, different to the one used at T1) became slightly stronger, whilst the relationship between Order WM and counting decreased by a considerable margin. The relationship between Daily events accuracy and Counting remained stable, and now Daily events accuracy was significantly related to performance on the number ordering task.

These results suggest that both numerical and non-numerical ordinal tasks used in the study were measuring the same underlying construct, suggesting that, at least to a certain extent, both the processing of numerical and non-numerical order are sub-served by common mechanisms involved in the processing of ordinal information. Unlike Attout et al. (2014), the current study found that Order WM performance was significantly related to Number ordering performance between the ages of 4 and 6, even though the children in their study were slightly older than the current sample.

Regarding the relationship between numerical ordering tasks, Number ordering and Counting were also significantly correlated with each other at T1. At T2, the relationship between the two measures became even stronger than in T1. Both tasks correlated significantly with Number comparison (reflecting shared mechanisms in the processing of numerical information), but neither task correlated with Non-symbolic addition at T1. At T2, Counting and Number ordering correlated with both magnitude tasks. It should be noted that reliability estimates were low for the Non-symbolic addition task at T1, suggesting that at this stage, children did not solve this task using similar strategies that they employed to solve the Number ordering and Number comparison tasks.

The correlations between the non-numerical tasks at both time points offer an insight into whether these tasks are necessarily measuring the same skills. At T1, scores on the OPQ were not related to any of the other non-numerical ordering tasks; the only significant relationship was between Order WM performance and Daily events task accuracy; however, this relationship disappeared at T2. These findings regarding the OPQ are surprising, given that the OPQ and Daily events tasks both involve the retrieval of a familiar sequence from long-term memory.

Regarding the relationship between magnitude and ordinal measures at T1, performance on the Non-symbolic addition task correlated with Daily events performance, whilst Number comparison performance was correlated with Daily events and Order WM performance. At T2, both Number comparison and Non-symbolic addition were correlated with Order WM, as well as with Daily events performance. Regarding numerical magnitude and ordinal tasks, at T1, Number comparison correlated with both Counting and Number ordering (Non-symbolic addition did not correlate with either measure), whilst at T2, both Number comparison and Non-symbolic addition correlated with Counting and Number ordering.

One final important point concerns the relationship between magnitude tasks. As proposed in the previous chapter, if the ANS is linked to the acquisition of symbolic number knowledge, and therefore is subsequently involved in early mathematical development, then one would expect performance on symbolic and non-symbolic magnitude tasks to be correlated, This was not found to be the case at either time-point. This result supports the argument that the systems responsible for processing numerical and non-numerical magnitude are unrelated, and therefore the ANS is not necessarily the precursor to the shift from approximate to exact numerical skills in maths development.

3.4.6 Intelligence and socioeconomic status were found to be important in early mathematical development

With the exception of Block design scores at T1, both intelligence and socioeconomic status were robustly correlated with maths at both time-points, which suggests that these domain-general factors are important in early numerical development. Children from lower socioeconomic backgrounds tended to perform worse in maths than their peers who came from a higher socioeconomic background. Furthermore, higher verbal and non-verbal intelligence scores were also linked to higher scores on the maths assessments. These results show how, even at the beginning of primary school, children's relative level of deprivation and their intellectual skills have some importance in terms of how these children perform in maths, even prior to when they begin formal testing.

Based on the findings of Sirin (2005), it would be reasonable to expect that the effect of socioeconomic status on maths achievement would be stronger in Study 2, and may also be linked to children's reading skills. Furthermore, based on other research (Deary, Strand, Smith & Fernandes, 2007; Roth et al., 2015; Strenze, 2007), it would be expected that intelligence would become even more strongly linked to maths achievement amongst older children, and also may be linked to reading performance.

Chapter 4: The role of numerical and non-numerical ordering skills in maths development among 8-11 year-old children

4.0 Introduction and outline of tasks

Whilst Study 1 focused on the development of numerical and non-numerical skills, and the role that these skills play during the first two years of formal education, the aim of the current study was to investigate the later development of these skills, amongst children aged between 8 and 11, to assess the extent to which these numerical and non-numerical skills are important to maths development amongst children who are in the latter stages of primary school education in Northern Ireland. The questions to be answered in this chapter are outlined in the preceding subsections.

The differences between the tasks used in Study 1 and Study 2 are outlined in Table 4.1. In terms of the basic and academic measures, both Vocabulary and Block design was measured using the WISC-IV, rather than the WPPSI-III used in Study 1. The Deprivation measure was the same as in Study 1, although Deprivation was measured using the postcode of the school, rather than the postcode of the participant, as was the case in Study 1. Maths ability was assessed using the age-appropriate MALT test (which was used in T2 of Study 1); The Hodder Group Reading Test (second edition) was used to measure children's reading ability. The Choice reaction time task was also the same as the one used in the previous study.

The same ordering tasks from the previous study were also included in the current study, with only a few differences. The Number ordering task from T2 in the previous study was used in this current study, as the cardordering task used in T1 would have been too easy for older children. Similarly, the Daily events task used in the previous study would have been easy for older children, so this was replaced by an Annual event ordering task, which included a sequence of nine different annual events (instead of the six daily events), although children still had to respond to the presentation of a triad of events. In the Order-Processing Questionnaire, some of the items were changed to make the questionnaire more age-appropriate for children of this age. The Order WM task was the same as the one used in the previous study.

In terms of the magnitude measures, The number comparison task used in this study involved the comparison of two digits presented simultaneously, rather than the version used in Study 1, in which children compared a target number to five. The Non-symbolic addition task used in Study 1 was replaced by a Block comparison task, which involved the comparison of small arrays of blocks (ranging from 1-9 in numerosity). Finally, the number line task now consisted of 0-100 and 0-1000 number lines, as opposed to the 1-10 and 1-20 number lines used in Study 1. Two additional tasks were included in Study 2 that had not been included in the previous study; a measure of visuo-spatial working memory (Backward matrices) and a measure of response inhibition (Stop-signal task).

Table 4.1. Table showing the difference in the tasks used in Studies 1 and 2

Task	Study 1 T1	Study 1 T2	Study 2
Intelligence	WPPSI-III (Vocabulary & Block design)	WPPSI-III (Vocabulary & Block design)	WISC-IV (Vocabulary & Block design)
Deprivation	NIMDM	Not measured	NIMDM
Number Ordering	Card-based production task	Computer-based verification task	Computer-based verification task
Symbolic magnitude	Compare presented digit to 5	Compare two simultaneously-presented digits	Compare two simultaneously-presented digits
Non-symbolic magnitude	Non-symbolic addition	Non-symbolic addition	Block comparison
Number line	1-10 & 1-20 scales	0-100 & 0-1000 scales	0-100 & 0-1000 scales
Counting	Counting up to 50; counting forwards and backwards	Counting up to 100; counting forwards and backwards	Not used
Order-Processing Questionnaire	8-item questionnaire	Not used	7-item questionnaire
Order working memory	Order WM	Order WM	Order WM
Temporal ordering	Daily events task	Daily events task	Annual events task
Baseline reaction time	Choice Reaction Time	Choice Reaction Time	Choice Reaction Time
Visuo-spatial working memory	Not measured	Not measured	Backward matrices
Inhibition	Not measured	Not measured	Stop-signal task
Reading	Not measured	Not measured	HGRT-II
Mathematical achievement	Composite test (TEMA-III & WJ-III	MALT 6	MALT 9 & 10

4.1 Study 2

4.1.1 Which skills predict maths amongst older children?

Since many studies of order-processing have attempted to answer the question of which skills are important to maths learning in the early years of primary school (e.g. Attout et al., 2014; Sasanguie & Vos, 2018) and studies involving older children have not included children who are close to leaving primary school (e.g. Attout & Majerus, 2018), the aim of this study was to investigate which skills are important to maths learning in older children. This age group was chosen in particular, because in the Northern Ireland educational curriculum, these children would be in the last stage of learning development that children undergo in primary school (Key Stage 2), in which the curriculum is geared towards preparing children, not only for their potential exams in their final year of primary school, but also to prepare them before they move to secondary school (Council for the Curriculum, Examinations and Assessment, 2007).

Although many studies have not investigated the role of order-processing with older children, Lyons et al. (2014) investigated the role of different numerical and non-numerical tasks across childhood (between the ages of 6-12). The authors found that numerical magnitude (measured by number comparison); numerical ordering ability (measured by number ordering) and Number line estimation skills were significant predictors of arithmetic skills amongst 8-11-year-old children. Non-symbolic comparison skills did not predict arithmetic at any stage of development. This suggests that numerical measures (and a measure of the accuracy of the mental number line) may play an important role in maths learning amongst older children, given that these children have had a few years' experience with using the symbolic number system. Based on these results, I would also predict that Number comparison and Number ordering tasks would play an important role in mathematical development amongst 8-11-year-olds in the current study.

In the current study, I also included a visuo-spatial ordering task and an inhibition task. The backward matrices task was included as a measure of visuo-spatial working memory, as visuo-spatial working memory skills haves been linked to maths ability in children (e.g., Friso-van den Bos et al., 2013; Peng et al., 2016), and deficits in visuo-spatial working memory have also been cited as a possible deficit associated with maths learning difficulties (Mammarella, Lucangelli & Cornoldi, 2010; Passolunghi & Mammarella, 2010, 2011; Passolunghi & Cornoldi, 2008) and in children with Developmental Dyscalculia (Mammarella et al., 2015; Szűcs et al., 2013). I predicted that visuo-spatial skills would be somewhat related to maths achievement amongst older children. However, as discussed in Chapter 1, it is possible that verbal working memory skills (as would be measured by the Order WM task) would be more strongly involved in maths performance amongst older children, given the evidence suggesting that early strategies for solving mathematical problems rely more on visuo-spatial skills, but that these strategies become more reliant on verbal skills as children develop (Bull, Epsy & Wiebe, 2008; Meyer, Salimpoor, Wu, Geary & Menon, 2010). Based on this, I predicted that visuo-spatial working memory skills would not be as strongly related to maths as verbal working memory skills (Order WM).

Response inhibition was also measured in the study, using the Stop-signal task. This measure was included as there is some evidence of a relationship between inhibition skills and maths (e.g. Allan et al., 2014; Friso-van den Bos et al., 2013; Jacob & Parkinson, 2014) and inhibition skills have also been found to underlie performance on non-symbolic comparison amongst older children (Gilmore et al., 2013). Based on these results, one prediction would be that inhibition should be strongly related to maths skills, as well as to Non-symbolic comparison, and if you control for inhibition skills, this would eliminate the link between maths and dot comparison.

4.1.2 Are ordering skills also predictive of other academic skills? (E.g. reading)

Although this question was not addressed in Study 1, it may be the case that ordering skills may be involved in the development of other academic skills. Indeed, the Order WM task was designed to assess children's ability to retain serial order information, and was originally used in studies of the development of literacy skills. For example, Majerus et al. (2006) found that performance on the Order WM task was strongly associated with vocabulary development in children between the ages of 4 and 6. Perez, Majerus and Poncelet (2012) found that order WM capacity longitudinally predicted reading development amongst young children, whilst the same authors (Perez, Majerus & Poncelet, 2013) reported that adults with dyslexia showed a deficit in order WM. It is possible that the link between domain-general order processing and other academic skills is specific to short-term memory mechanisms, but the results from Study 1 suggest that it might be useful to examine whether such a link also extends to order-processing skills measured in this study. This issue will be addressed in the current study, by examining whether reading abilities are predicted by any of the ordering measures. Given that the Order WM task has previously been found to predict reading skills, it was hypothesized that this task, at the very least, would predict older children's reading abilities.

4.2 Method

4.2.1 Participants

One hundred primary school students who attended year 5, 6, or 7 were recruited from eight primary schools in Northern Ireland (range: 8 years 4 months – 11 years 1 month; mean age = 9 years and 8 months, *SD* = 8.99 months, 58 girls, 43 students attended year 5, 40 year 6 and 17 year 7). The schools represented a mix of urban schools and outlying rural schools. There were 14 children in the sample who did not speak English as their first language. Nevertheless, the researchers judged that these children had appropriate English skills to be able to participate in the study. Informed consent was obtained from the schools and the parents of all children who participated. The study received ethical approval from the School of Psychology Ethics committee.

4.2.2 Materials

4.2.2.1 Measures of socio-economic status

The *Multiple Deprivation Measure* (MDM) was used in Study 1 and the current study (see Chapter 3 section 3.1.2). In the current study, I used the schools' postcodes rather than the postcodes of each individual child, although in the case of rural schools, the two are likely to be the same.

In addition to the postcode-based deprivation measure, another indicator of children's socio-economic background is their eligibility to *free school meals*. Children in Northern Ireland are entitled for free school meals if their parent/guardian experiences economic hardship. Nevertheless, FSM pupils are not the same set of children with the lowest household incomes (Hobbs & Vignoles, 2010). Apart from financial difficulties, other reasons for FSM eligibility might include children having special dietary needs, or if their parent/guardian is an asylum seeker. However, in the Northern Irish context, most children are eligible for FSM due to low household income.

IQ measures

A short form of the *Wechsler Intelligence Scale for Children-fourth edition* (WISC-IV UK; Wechsler, 2003) that consisted of the block design (non-verbal) and vocabulary (verbal) subtests was individually administered to each participant. This combination of subtests has the highest validity and reliability of the two-subtest short forms of the WISC, and, on the basis of these tasks, full-scale IQ scores can be estimated using the method outlined by Sattler and Dumont (2004).

4.2.2.2 Order processing measures

A short questionnaire, the *parental Order Processing Questionnaire* (OPQ), was administered to obtain parents' ratings of their child's ability to perform everyday tasks that involve order processing (see Appendix B). The questionnaire was an adapted version of the scale used by O'Connor, Morsanyi and McCormack (2018[6]). As the original scale was developed for 5-year-olds, some items were modified to make them appropriate for older children. Parents were asked to rate on a 7-point Likert scale (ranging from 1 = totally disagree to 7 = totally agree) a list of seven statements referring to everyday ordering tasks, such as remembering schedules, planning sequential actions, and carrying out tasks in the appropriate order. Example statements are: "My son/daughter can easily adjust to changes in routine", or "My son/daughter is able to plan a sequence of activities independently". A sum score was computed for the scale. In the present sample, Cronbach's alpha was .82.

The same *order working memory task* (animal race), based on Majerus, Poncelet, Greffe, and van der Linden (2006), was administered that was also administered in Study 1 (see Chapter 3, section 3.1.2.1). In this version, a span score was also computed, based on the length of the list that the child could recall. To have a span score of 3, a child had to be able to reconstruct at least two out of the four lists with three items correctly. In the present sample, the split-half reliability of the total score (using the Spearman-Brown formula to compare performance on the first two vs. the second two trials at each set length) was .94.

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[6] See Appendix Q

A computerized version of the *backward matrices task* was administered to measure visuo-spatial working memory (based on Mammarella, Hill, Devine, Caviola, & Szűcs, 2015). The task involves remembering the location and the order of blue squares displayed sequentially in a 4X4 grid on a computer screen. The children were asked to recall the location of the blue squares in reverse order. The number of squares in the sequence was successively increased from two to eight. Two practice trials were presented, followed by 14 experimental trials (two trials at each sequence length). A point was given to the child for each sequence that was correctly recalled. Additionally, a span score was computed based on the number of locations that the child was able to recall in the correct order. To have a span score of 3, a child had to be able to recall at least one out of the two three-item sequences correctly. In the present sample, the split-half reliability (using the Spearman-Brown formula to compare performance on the first vs. second trial at each sequence length) was .71.

A computerized task was designed to measure *numerical ordering ability* (based on Lyons & Beilock, 2011). In this task, children were presented with number triads (e.g., 2 3 7) and they were asked to decide whether the numbers were in increasing order from left to right, irrespective of the numerical distance between the numbers. All numbers were between 1 and 9. Four practice trials were presented, followed by 48 experimental trials (based on Morsanyi, O'Mahony & McCormack, 2017). Cronbach's alpha for the sample was .91 for accuracy and .95 for RT.

Another computerized task was designed to measure *annual event ordering ability* (based on Friedman, 2002). In this task, children were presented with three pictures referring to special days or events during the year (e.g., Easter, Halloween and Christmas), and they were asked to indicate whether the events were in the right order from left to right, the way they happen during one calendar year. The nine events presented were Valentine's day, Easter, sports day (held by the schools in June every year), summer holiday, going back to school after the summer holiday, Halloween, Christmas, New Year's Eve and the child's birthday. As in the number ordering task, four practice trials were presented, followed by 48 experimental trials. Cronbach's alpha for our sample was .88 for accuracy and .94 for RT.

The trials in the number ordering task and the event ordering task were matched so that for each number ordering trial there was a corresponding event ordering trial. The number triad 2, 3, 8, for example, corresponds to the event triad Easter, sports day and Christmas because Easter is the second event happening during the year, sports day the third event and Christmas the eighth event. The trials in both tasks were designed so that the distance between the two extreme numbers/events within each triad was systematically manipulated. The smallest distance was 2 (three consecutive numbers/events) and the largest distance was 7. For each distance eight trials were presented in each task (four in the correct order and four in mixed order). Triads including the two extreme numbers and events were not included to avoid the possibility that participants respond to these trials using a response rule that does not necessitate the checking of order within the triads. Additionally, to ensure that participants process all three items within the triads, in the case of mixed order triads the first two items always appeared in the correct order. Accuracy and reaction times were recorded in both tasks. Following Lyons et al. (2014) and Goffin and Ansari (2016) we used a composite of error rates (ER) and RTs (correct trials only) to index performance on these tasks. The measures were combined according to the formula: P = RT (1 + 2ER), where a higher value indicates worse performance. This formula seems appropriate, because in the case of very high levels of accuracy the results basically reflect RTs only. Lyons et al. (2014) justified their choice of multiplying error rates by 2 in their formula on the basis that their task (just as ours in the current study) included binary forced choices (ER = .5 indicates chance).

4.2.2.3 Magnitude and estimation measures

A computerized task was designed to measure *symbolic number comparison ability* (based on that of Dehaene, Dupoux & Mehler, 1990). Children were presented with two one-digit numbers, one on the left side of the screen and the other one on the right side of the screen, and they were asked to indicate which number was larger. All numbers were between 1 and 9. Four practice trials were administered followed by 48 experimental trials. Cronbach's alpha for our sample was .95 for accuracy and .95 for RT. We used the same formula as for the number ordering and annual event ordering tasks to create composite scores from accuracy and reaction time results.

Another computerized task was developed to measure *non-symbolic comparison ability* (modelled on the task used by Price, Holloway, Räsänen, Vesterinen & Ansari, 2007). Children were presented with two arrays of blocks, one array on the left side of the screen and the other array on the right side of the screen, and they were asked to indicate which array contained more blocks. All arrays contained between 1 and 9 blocks. The stimuli were created in such a way that continuous quantity variables such as area and density of the squares could not be reliably used to select the correct array. Additionally, on half of the trials, the array with more blocks had a bigger total surface area (congruent trials), and in the other half the array with more blocks had a smaller total surface area (incongruent trials). The numerical difference between the two arrays was systematically manipulated between 1 and 6, and, for each difference, eight trials were presented. The task was presented as a game in which the arrays showed how many blocks each of two children had (this was modelled on Gilmore, Attridge, De Smedt, & Inglis, 2014). The arrays were presented for 1 second, after which they disappeared from the computer screen. Once the blocks disappeared from the screen, the children were prompted to indicate which of the two characters had more blocks. Four practice trials were presented, followed by 48 experimental trials. In the present sample, Cronbach's alpha was .58 for accuracy.

A computerized version of the *number line estimation task* was administered to assess children's ability to spatially represent numbers along a mental number line. This task was based on the number-to-position problems used by Siegler and Opfer (2003). In each problem, children were presented with a number and asked to estimate where it would appear on a number line. We used 2 different scales for the task. The first scale ranged from 0 to 100 and the second scale ranged from 0 to 1000. Both scales were

1000 pixels long, which made the errors of estimation (i.e. the distance in pixels between the correct position of the target number and children's estimation of the position of the number) across scales directly comparable. The task included 10 problems for each scale. The numbers presented were 2, 3, 4, 6, 18, 25, 42, 67, 71 and 86 for the 0-100 scale and 4, 6, 18, 25, 71, 86, 230, 390, 780, 810 for the 0-1000 scale. Estimation errors were averaged across all 10 trials per scale, with a higher number indicating worse performance. In our sample, Cronbach's alpha was .67.

4.2.2.4 Additional measures

The *stop signal task* (Logan & Cowan, 1984) was administered to measure response inhibition. In the task, a smiley face was presented on a black background in the middle of the screen. The smiley face was followed by a white arrow, which was pointing left or right. The presentation of the arrow was followed by either a sound, the stop signal, or no sound. Children were required to indicate the direction of the arrow using a key press during "go" trials, and to withhold their response during "stop" trials. A block of 30 go trials was administered first to calculate the mean RT of the child. This was followed by 140 alternately go and stop trials presented in three blocks of 28, 56 and 56 trials. The first of these three blocks was considered a practice block. Only the results of the other two blocks were used in the analyses. The stop signal was presented at four different intervals: 200, 300, 400, and 500 ms before the mean RT of the child, calculated on the basis of the first block of go trials. Twelve trials of each interval were administered in total in the last two blocks leading to a proportion of stop trials of 30%.

Mean accuracy of the stop trials in block 3 and 4 were calculated as a measure of performance. Cronbach's alpha for our sample was .83.

A *choice reaction time task* (based on Fry & Hale, 1996) was administered to measure basic processing speed. Children were asked to press a red or a blue button in response to the presence of a red or a blue circle on the computer screen. Forty trials were administered (half of them with a red circle and the other half with a blue circle). Performance was indexed by children's mean reaction time for correct trials. Cronbach's alpha for the present sample was .92.

4.2.2.5 Standardized mathematics and reading measures

The *Mathematics Assessment for Learning and Teaching test* (MaLT; Williams, 2005) is a group-administered written test. The MaLT was developed in accordance with the National Curriculum and National Numeracy strategy for England and Wales. Test items cover: counting and understanding number, knowing and using number facts, calculating, understanding shape, measurement, and handling data. I administered two versions of the task with different difficulty levels. MaLT test 9 for children attending year 5 and MaLT test 10 for children attending year 6 and 7. The MaLT test was standardized in 2005 with children from 120 schools throughout England and Wales (MaLT 9, $\alpha = .93$; MaLT 10, $\alpha = .92$). Children had to complete the test within 45 minutes.

The *Hodder Group Reading Test-II* (HGRT-II; Vincent & Crumpler, 2007) is a group-administered multiple-choice test that assesses children's reading of words, sentences and passages. The HGRT-II test was standardized in 2005 with children from 111 primary and secondary schools throughout England and Wales (HGRT-II, level 2, $\alpha = .95$). Children had to complete the test within 30 minutes.

4.2.3 Procedure

The participants completed the tasks in three testing sessions. The order in which the tasks were presented was the same for all participants. The first session was a group session, which took approximately 80 minutes. In this session, the participants were administered the MaLT and the HGRT-II. The other two sessions were individual sessions of about 35 minutes. In the first individual session, the children completed the following tasks (in this order): backward matrices, choice RT, annual event ordering, symbolic comparison, and order working memory. The second individual session started with the number line estimation task. This was followed by number ordering, the stop signal task, non-symbolic comparison, and the two subtests of the WISC-IV: block design and vocabulary. On average, there were 14 days between the group session and the first individual session, and 9 days between the first individual session and the second individual session.

4.3 Results

4.3.1 Descriptive statistics

Descriptive statistics for each measure are presented in Table 4.1. In the current sample deprivation scores ranged from 14.82 to 67.23, with a median score of 29.68, indicating that the areas where the children lived were mostly characterised by medium-to-low levels of deprivation. Nevertheless, there were 43 children (i.e. 43% of the sample) who were eligible for free school meals (FSM), which is higher than the average figure for Northern Ireland (30.6% according to the 2015-2016 Census; Northern Ireland Statistics and Research Agency, 2016). Children's estimated full scale IQ scores were found to be within the normal range (Mean IQ score = 96.59, *SD* = 14.68). Parents tended to rate their children reasonably high in terms of their ability to perform everyday tasks that involve order processing (children's mean score on the OPQ was 40.42 out of 49). In the Order WM task, children were able to recall on average 13.88 sequences, which corresponded to an average serial order memory span of 4.54 items (*SD* = .96). In the Visuo-spatial WM task, children were able to recall on average 5.89 sequences, which corresponded to an average visuo-spatial working memory span of 4.74 items (*SD* = 1.41). Children could reliably pass the easier levels of the Visuo-spatial WM task, but failed when the task became more difficult. Children performed better on the Number ordering task compared to the Annual event ordering task. Children showed very good performance on the Number comparison and Block comparison tasks. Accuracy scores on the Block comparison task were in fact close to ceiling. In the Number line estimation task children's average estimation error for the 0-100 scale was 4.70 pixels (*SD* = 2.21), whilst their average estimation error for the 0-1000 scale was 11.80 pixels (*SD* = 6.94).

Table 4.2. Descriptive statistics for all measures.

Measure	**Min.**	**Max.**	**Mean *(SD)***
Multiple Deprivation Measure	14.82	67.23	Median = 29.68
Free school meals (0=no; 1=yes)	0	1	.43 *(.50)*
Vocabulary (WISC-IV raw score)	16	51	29.86 *(7.24)*
Block design (WISC-IV raw score)	6	59	27.32 *(9.50)*
Estimated full scale IQ	71	144	96.59 *(14.68)*
Order Processing Questionnaire	17	49	40.42 *(6.49)*
Order working memory	1	21	13.88 *(3.74)*
Visuo-spatial working memory	1	11	5.89 *(2.09)*
Number ordering (acc.)	.46	1.00	.90 *(.13)*
Number ordering (RT)	1110.13	8488.51	2718.29 *(1193.83)*
Annual event ordering (acc.)	.46	1.00	.77 *(.17)*
Annual event ordering (RT)	1303.10	9149.44	4129.60 *(1605.56)*
Number comparison (acc.)	.44	1.00	.92 *(.14)*
Number comparison (RT)	545.65	2210.96	999.74 *(303.14)*
Block comparison (acc.)	.65	1.00	.93 *(.05)*
Number line estimation (error)	2.22	16.39	8.25 *(3.80)*
Stop signal (acc.)	.42	1.00	.86 *(.12)*
Choice RT (RT)	350.25	1056.03	566.94 *(121.38)*
HGRT-II (raw score)	11	51	33.26 *(10.06)*
MaLT (raw score)	4	41	20.77 *(8.02)*

Note: RT = reaction time (in ms); acc. = accuracy. Task abbreviation: WISC-IV: Wechsler Intelligence Scale for Children-fourth edition; HGRT-II: Hodder Group Reading Test-II; MaLT: Mathematics Assessment for Teaching and Learning Test.

Table 4.3. Descriptive statistics for all measures, by school year

Measure	Year 5 Mean *(SD)*	Year 6 Mean *(SD)*	Year 7 Mean *(SD)*
Multiple Deprivation Measure	30.77 *(13.06)*	34.61 *(16.36)*	47.35 *(19.32)*
Free school meals (0=no; 1=yes)	.35 *(.48)*	.48 *(.51)*	.53 *(.51)*
Vocabulary (WISC-IV raw score)	30.05 *(8.44)*	29.55 *(5.91)*	30.12 *(7.22)*
Block design (WISC-IV raw score)	27.86 *(9.90)*	26.33 *(9.24)*	28.29 *(9.47)*
Estimated full scale IQ	103.14 *(15.84)*	92.38 *(10.94)*	89.94 *(13.29)*
Order Processing Questionnaire	40.30 *(6.29)*	40.53 *(5.99)*	40.47 *(8.32)*
Order working memory	13.35 *(3.77)*	14.23 *(2.89)*	14.41 *(3.97)*
Visuo-spatial working memory	5.37 *(1.94)*	6.15 *(1.93)*	6.59 *(2.60)*
Number ordering (acc.)	.87 *(.15)*	.90 *(.12)*	.95 *(.06)*
Number ordering (RT)	3191.81 *(1320.73)*	2513.96 *(1033.00)*	2001.30 *(621.00)*
Annual event ordering (acc.)	.75 *(.17)*	.76 *(.17)*	.82 *(.15)*
Annual event ordering (RT)	4929.61 *(1889.72)*	3706.75 *(1125.30)*	3100.97 *(445.47)*
Number comparison (acc.)	.90 *(.16)*	.94 *(.12)*	.92 *(.15)*
Number comparison (RT)	1124.12 *(384.23)*	906.06 *(154.88)*	905.55 *(222.80)*
Block comparison (acc.)	.93 *(.06)*	.94 *(.05)*	.95 *(.04)*
Number line estimation (error)	9.59 *(3.81)*	7.26 *(3.55)*	7.21 *(3.44)*
Stop signal (acc.)	.86 *(.11)*	.87 *(.10)*	.84 *(.16)*
Choice RT (RT)	588.04 *(116.21)*	549.48 *(108.84)*	554.66 *(157.22)*
HGRT-II (raw score)	30.14 *(10.10)*	35.03 *(9.10)*	37.00 *(8.37)*
MaLT (raw score)	18.67 *(7.55)*	21.18 *(7.33)*	25.12 *(9.25)*

Note: RT = reaction time (in ms); acc. = accuracy. Task abbreviation: WISC-IV: Wechsler Intelligence Scale for Children-fourth edition; HGRT-II: Hodder Group Reading Test-II; MaLT: Mathematics Assessment for Teaching and Learning Test

4.3.2 Age comparisons

A 3x10 mixed ANOVA was performed, with all measures in the study as the dependent variables (OPQ scores, Order WM scores, Visuospatial WM scores, Number ordering, Annual events, Number comparison, Block comparison, Number line performance, Stop-signal task performance and Baseline RT), and school year (5, 6, or 7) as the independent variable. Descriptive statistics for each measure, by age group, are included in Table 4.2.

Amongst the basic measures, the analysis revealed a main effect of school year on Multiple deprivation scores; $F(2, 97) = 6.93$, $p = .002$, $\eta_p^2 = .125$. Bonferroni-corrected multiple comparisons revealed that children in year 5 (mean deprivation score = 30.77) had significantly lower deprivation scores compared to children in year 7 (mean deprivations score = 47.35; $p = .001$) and children in year 6 (mean deprivation score = 34.61; $p = .001$) had significantly lower deprivation scores compared to children in year 7. There were no main effects of school year on Vocabulary or Block design raw scores.

Amongst the ordinal tasks, the analysis revealed a main effect of school year on Number ordering RT's; $F(2, 97) = 8.03$, $p = .001$, $\eta_p^2 = .142$. Bonferroni-corrected multiple comparisons revealed that children in year 5 (mean RT = 3191.81 ms) were significantly slower in task performance compared to children in year 6 (mean RT = 2513.96 ms; $p = .021$) and year 7 (mean RT = 2001.30 ms; $p = .001$). There was also a main effect of school year on annual events task RT's; $F(2, 97) = 12.61$, $p < .001$, $\eta_p^2 = .206$. Children in year 5 (mean RT = 4929.62 ms) were significantly slower in task performance compared to children in year 6 (mean RT = 3706.29 ms; $p = .001$) and year 7 (mean RT = 3100.97 ms; $p < .001$).

For the magnitude tasks, there was a main effect of school year on Number comparison RT's; $F(2, 97) = 7.14$, $p < .001$, $\eta_p^2 = .128$. Children in year 5 (mean RT = 1124.12 ms) were significantly slower in task performance compared to children in year 6 (mean RT = 906.06 ms; $p = .002$) and year 7 (mean RT = 905.54 ms; $p = .027$). Finally, there was also a main effect of school year on Number line estimations; $F(2, 97) = 5.05$, $p = .008$, $\eta_p^2 = .094$. Bonferroni-corrected multiple comparisons revealed that children in year 5 (mean error = 9.59) made estimations that were significantly further away from the position of the target number, compared to children in year 6 (mean error = 7.26; $p = .014$).

4.3.3 Correlational analyses

4.3.3.1 Zero-order correlations between all measures and maths ability

Correlations between the different measures are outlined in Table 4.4. As it could be expected, performance on several tasks increased with age[7].

Higher deprivation scores were significantly related to lower performance on the Vocabulary subtest of the WISC-IV. This same result was found in Study 1 at both time-points. Deprivation scores also negatively correlated with Order WM, which was also found at T2 in Study 1.

[7] In the case of the maths and reading tests, age-adjusted standard scores were used, and for this reason no relationship with age was expected.

Vocabulary scores were significantly correlated with Block design (similar to T2 in Study 1), Order WM (also the case at both time-points in Study 1), Number line estimation (this was not found at either time-point in Study 1), Stop signal task accuracy, reading and maths scores (which was also found at both time-points in Study 1).

Block design scores were significantly related to Visuo-spatial WM accuracy, Number line estimation (this was also found at T2 in Study 1), Math scores (also found at T1 and T2) Block design scores were also related to reading scores. Finally, Choice RT scores were significantly related to all tasks that required fast responding (i.e., Number ordering, Annual event ordering and Number comparison), as well as to math scores.

Regarding the relationships between the five order processing measures, there was a very strong relationship between the number and the Annual event ordering tasks (a similar finding was observed between Daily events and Number ordering tasks in Study 1 at T1 and T2), and performance on the Annual event ordering task was also related to Visuo-spatial WM.

The OPQ and Order WM measures were not related to any other order processing task in this study (in Study 1, the OPQ was related to Number ordering at T1, whilst the Order WM correlated with all other order-processing tasks, except for Daily events performance at T1).

In terms of the relationships between the three magnitude-processing measures, only Number comparison and Number line estimation (i.e., the measures including symbolic numbers) were significantly correlated (this was not found to be the case in Study 1). Block comparison was not related to the two other magnitude-processing measures (in Study 1, Non-symbolic addition also did not correlate with either Number comparison or Number line performance).

Finally, regarding the relationships between the order processing and magnitude-processing tasks, performance on the Number comparison task was significantly correlated with all order processing measures, except for the OPQ (in Study 1, Number comparison performance also correlated with the order-processing measures used, except for the OPQ).

Performance on the Block comparison task was significantly related to all order processing measures, except for the Visuo-spatial WM task (In Study 1, Non-symbolic addition performance only correlated with Daily events accuracy at T1; at T2, Daily events performance was the only order-processing measure that Non-symbolic addition did not correlate with).

Regarding the link between inhibition, non-symbolic magnitude-processing skills and maths achievement, the analyses showed that Stop-signal accuracy was somewhat related to maths achievement ($r = .24$), and Block comparison accuracy was also related to maths ($r = .27$), although the relationship between Stop-signal and Block comparison tasks was non-significant ($r = .04$), suggesting that inhibition skills are not strongly linked to non-symbolic magnitude-processing skills. To investigate the nature of this relationship further, correlation analysis was conducted on congruent and incongruent trials of the Block comparison task separately, to investigate whether the observed relationship between non-symbolic skills and maths achievement was driven by performance on incongruent trials, as this was the case in Gilmore et al. (2013). Consistent with the finding of

Gilmore et al., the analysis revealed that performance on incongruent trials (r = .25), but not on congruent trials (r = .11), was significantly correlated with maths performance. Finally, to investigate whether inhibition skills explained the link between non-symbolic magnitude and maths achievement, a partial correlation was conducted between children's performance on incongruent trials in the Block comparison task and maths achievement, whilst controlling for performance on the Stop-signal task. The analysis revealed that the relationship between non-symbolic magnitude skills and maths achievement remained significant, even after controlling for inhibition skills; r (97) = .26, p = .009.

Performance on the Number line estimation task was significantly correlated with Number ordering and Annual event ordering (Number line performance did not correlate with any of the order-processing measures in Study 1).

Math scores were significantly correlated with two out of the four order processing measures (i.e., Order WM and Number ordering), as well as correlating with all magnitude-processing measures (i.e., Number comparison, Block comparison and Number line estimation), and with performance on the Stop signal task. Additionally, there was a very strong relationship between maths achievement and reading scores.

Given that our mathematics measure assessed various skills (i.e., counting and understanding number, knowing and using number facts, calculating, understanding shape, measurement, and handling data), we also conducted separate correlational analyses between these aspects of mathematics knowledge and the other study variables (Appendix H)[8]. The results were consistent with the findings regarding overall maths performance: the tasks that were related to maths skills in general were also related to (almost) all type of maths skills.

4.3.3.2 Bootstrap correlations between all measures and maths ability

A bootstrap procedure (using 10,000 samples) was also applied to assess the reliability of the relationships between each measure and math scores. This procedure allowed for a 95% confidence interval to be computed for the correlations (see Figure 1). If a measure was found to have a significant bootstrap correlation with math, it was considered to be robustly related to math performance. Figure 4.1 shows that the measures that had previously shown significant zero-order correlations with math also showed significant zero-order bootstrap correlations.

4.3.3.3 Partial correlations between all measures and maths ability

Fifth-order partial correlations between all measures after controlling for age, deprivation (MDM), IQ (block design and vocabulary) and Choice RT performance showed that maths scores remained significantly related to Order WM, Number ordering, Block comparison, Number line estimation and reading scores. However, math scores were no

[8] Given that some children completed the MALT 9 (*n*=66) and others completed the MALT 10 (*n*=34), and the two versions of the test included a different number of items related to each maths skill, I converted children's scores for each skill into z scores, and used the z scores as outcome measures.

longer related to performance on the number comparison and stop signal tasks.

After controlling for age, deprivation, IQ and choice RT, the relation between Annual event ordering and Number ordering remained strong. The relation between the Annual event ordering task and the Visuo-spatial WM task was no longer significant. The relationship between Number comparison and Number line estimation also remained significant. Regarding the relationships between the order-processing measures and magnitude-processing measures, the relations between Number comparison and Number ordering, Block comparison and the OPQ, and Block comparison and number ordering remained significant. Performance on the Number line estimation task was no longer related to performance on any order processing measure after controlling for the covariate measures.

4.3.3.4 Zero-order correlations between all measures and reading ability

As shown in Table 4.4, reading scores were significantly correlated with IQ measures (Vocabulary and Block design); numerical and non-numerical ordering skills (OPQ, Order WM and Number ordering); non-symbolic magnitude (Block comparison); estimation skills (Number line) and maths (MALT scores).

4.3.3.5 Bootstrap correlations between all measures and reading ability

The same bootstrap procedure (outlined in section 4.3.3.2) was applied to assess the reliability of the relationships between each measure and reading scores. Figure 4.2 shows that the measures that had previously shown significant zero-order correlations with math also showed significant zero-order bootstrap correlations.

4.3.3.6 Partial correlations between all measures and reading ability

After controlling for Vocabulary and Block design scores, Deprivation scores, Age and Choice reaction times, reading scores remained significantly related to scores on the OPQ, Order WM, Number ordering, Number line estimation tasks and maths achievement. Reading scores also became significantly related to Annual event ordering. Reading scores were no longer related to performance on the Block comparison task.

Table 4.4. Zero-order correlations between all measures

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
1. Age	-															
2. MDM	.11	-														
3. Vocabulary (raw score)	.03	-.24*	-													
4. Block design (raw score)	-.02	-.07	.36**	-												
5. OPQ	-.03	.11	.12	-.06	-											
6. Order WM	.03	-.24*	.40**	.18	.06	-										
7. Visuo-spatial WM	.26**	-.03	.15	.27**	.12	.01	-									
8. Number ordering[a]	.35**	.16	-.01	.10	-.03	.15	.17	-								
9. Annual event ordering[a]	.37**	.12	-.04	.07	.05	.12	.20*	.60**	-							
10. Number comparison[a]	.33**	-.15	.04	.09	.02	.22*	.22*	.41**	.34**	-						
11. Block comparison	.17	.11	.15	.11	.22*	.22*	.02	.31**	.20*	.14	-					
12. Number line estimation	.30**	-.08	.22*	.20*	.12	.17	.16	.26**	.23*	.34**	.13	-				
13. Stop signal	-.02	-.05	.21*	.09	.02	.03	.04	.11	.01	.02	.04	.11	-			
14. Choice RT	.15	-.06	.09	-.06	-.05	.17	.03	.39**	.33**	.40**	.17	.19	.12	-		
15. HGRT-II	-.13	-.17	.55**	.25**	.27**	.47**	.14	.20*	.12	.11	.21*	.27**	.15	.15	-	
16. MaLT	-.10	-.11	.48**	.41**	.15	.48**	.04	.30**	.16	.22*	.27**	.35**	.24*	.27**	.60**	-

Note: Higher scores on each task indicate better performance. [a] Performance on these tasks was indexed by a composite score created from accuracy and reaction times (the formula is described in the Method section). Task abbreviation: MDM: Multiple deprivation measure; OPQ: order processing questionnaire; WM: working memory; HGRT-II: Hodder Group Reading Test-second edition; MaLT: Mathematics assessment for Learning and Teaching Test * $p < .05$, ** $p < .01$.

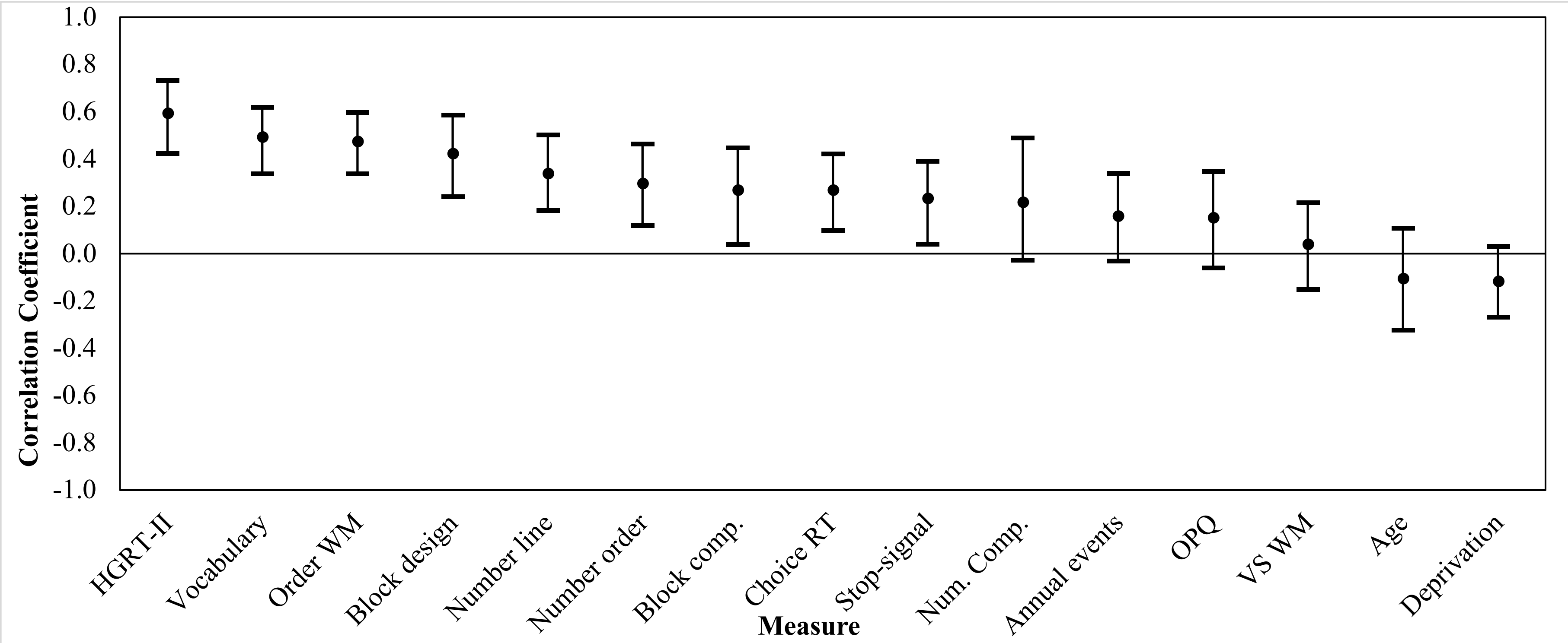


Figure 4.1. 95% bootstrap confidence intervals for zero-order correlations between each measure and math scores. *Task abbreviation: Comp: comparison; MDM: multiple deprivation measure; OPQ: order processing questionnaire; VS: Visuo-spatial; WM: working memory; HGRT-II: Hodder Group Reading Test-second edition.*

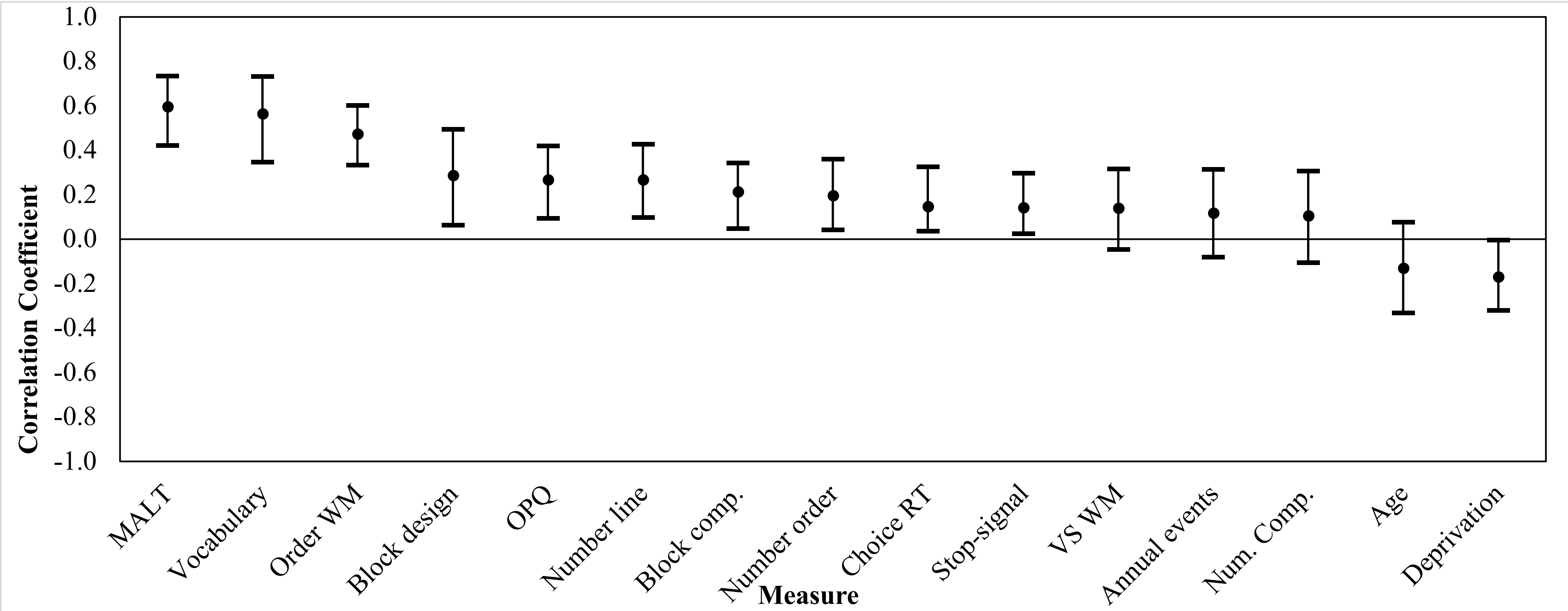


Figure 4.2. 95% bootstrap confidence intervals for zero-order correlations between each measure and reading scores. Note: Higher scores on each task indicated better performance. Task abbreviation: Comp: comparison; MALT: Mathematics Assessment for Learning and Teaching; MDM: multiple deprivation measure; OPQ: order processing questionnaire; VS: Visuo-spatial; WM: working memory.

4.3.4 Regression analyses predicting maths and reading ability

The regression analyses regarding the relationship between the predictor variables and math performance followed a similar procedure to that of Szűcs, Devine, Soltész, Nobes and Gabriel (2014) and O'Connor et al. (2018). The variables that both had a significant bootstrap correlation and a significant partial correlation with math performance were entered first. The backward procedure was used to remove predictors with a p value of .10 or above. Once non-significant predictors were removed, the five covariates (age, deprivation, vocabulary, block design and choice RT) were entered into the model, one by one, to examine whether they changed the significance of the predictors and improved fit. The model that explained the greatest proportion of variance, with only significant predictors was selected as the final model.

In the regression model predicting maths achievement, Order WM, Number ordering, Block comparison, and Number line estimation were entered into the initial model. After block comparison was removed, the model had a significant fit ($F(3, 98) = 15.78$, $p < .001$), and it explained 31% of the variance in maths performance.

When the covariates (age, deprivation, vocabulary, block design, and choice RT) were added to the regression model one by one, this resulted in a final model ($F(5,94) = 20.76$, $p < .001$) with five significant predictors: Number ordering, Order working memory, Number line estimation, Vocabulary and Block design, which explained 50% of the variance in maths achievement. Deprivation, age and Choice RT were non-significant predictors and therefore removed from the model. Table 4.5 shows the final regression model.

In the regression model predicting reading skills, OPQ scores, Order WM, Number ordering, Block comparison, and Number line estimation were entered into the initial model. After Block comparison, Number line estimation and Number ordering were removed, the model had a significant fit ($F(2, 97) = 19.15$, $p < .001$), and it explained 22% of the variance in maths performance.

When the covariates (age, deprivation, vocabulary, block design, and choice RT) were added to the regression model one by one, this resulted in a final model ($F(3,96) = 26.11$, $p < .001$) with three significant predictors: OPQ scores, Order working memory and Vocabulary scores, which explained 43% of the variance in children's reading skills. Deprivation, age, Block design and Choice RT were non-significant predictors and therefore removed from the model. Table 4.6 shows the final regression model.

Table 4.5. Measures significantly predicting maths scores. *(R^2 = .50, F(5, 94) = 20.76, p < .001)*

	Predictors	***B***	***β***	***p***	**B** [95% CI]	***R²***	***Adj. R²***
Model 1	Order WM	1.34	.41	.001	.86 - 1.95	.33	.31
	Number ordering [a]	<.001	-.18	.037	-.001 - -.00005		
	Number line	-.70	-.23	.012	-1.19 - -.21		
Model 2	Order WM	.82	.26	<.001	.36 – 1.37	.53	.50
	Number ordering [a]	-.001	-.26	.001	-.001 - -.0004		
	Number line	-.60	-.20	.008	-1.02 - -.18		
	Vocabulary	1.20	.33	<.001	.62 – 1.79		
	Block design	.88	.21	.009	.118 – 1.63		

Note: [a] Performance on this task was indexed by a composite score created from accuracy and reaction times (the formula is described in the Method section).

Table 4.6. Measures significantly predicting reading scores.

(R^2 = .43, $F(3, 96) = 26.11$, $p < .001$)

	Predictors	***B***	***β***	***p***	**B** [95% CI]	***R²***	***Adj. R²***
Model 1	Order WM	1.89	.46	<.001	1.18 – 2.66	.23	.22
	OPQ	.53	.24	.006	.23 - .83		
Model 2	OPQ	.45	.20	.009	.14 – .74	.45	.43
	Order WM	1.26	.31	<.001	.68 - 1.93		
	Vocabulary	1.98	.44	<.001	1.01 – 2.83		

4.4 Discussion

This study explored the role of ordering and magnitude-processing abilities in mathematics achievement in children in the final years of primary school. Of particular interest was investigating the relative contribution of magnitude and ordering skills to mathematics achievement, while also considering socio-economic status, age, IQ and inhibition skills.

The age comparisons revealed that younger children performed worse than older children in numerical ordering (Number ordering); non-numerical ordering (Annual events); numerical magnitude (Number comparison), and estimation skills (Number line), suggesting that these skills are still developing even at the later stages of primary school education. Younger children had lower deprivation scores than children 1 and 2 years older than them. Although even though older children tended to be more deprived than younger children, nonetheless the age effects in these cognitive tasks suggests that these numerical and non-numerical skills are relatively independent of children's family background, suggesting that the maths education received by children in these schools was doing a good job in improving these basic skills.

The correlation analysis revealed that the order-processing (with the exception of Visuo-spatial WM and OPQ scores) and magnitude measures were robustly related to maths achievement amongst 8-11-year-olds, showing that these skills were important to later numerical development. Order-processing (with the exception of Visuo-spatial WM and Annual events) and magnitude measures (with the exception of Number comparison) were robustly related to reading skills, showing the importance of these skills to reading development amongst older children.

The regression analyses revealed that Number ordering and Order WM performance were amongst the strongest predictors of mathematics skills. Number line estimation was also a significant predictor of maths. These tasks independently predicted maths skills, after also controlling for the effects of children's age, socioeconomic status, processing speed and verbal and non-verbal intelligence. This suggests that ordering and estimation skills explained variance in children's maths achievement, after controlling for several domain-general factors, highlighting the importance of these skills in how older children solve mathematical problems.

After also controlling for the effects of children's age, socioeconomic status, processing speed and verbal and non-verbal intelligence, the regression analysis revealed that OPQ scores and Order WM performance were significant predictors of children's reading ability, even when accounting for the variance explained by Vocabulary scores. This suggests that order-processing skills are also involved in the development of other academic skills, opening up a potential new area of research on the importance of ordering skills to the development of academic aptitude.

4.4.1 Ordinality (and estimation skills) were found to be more important to maths development amongst 8-11 year old children, in comparison to magnitude

The results of Study 1 showed that non-numerical ordering skills were initially the best predictor of maths achievement at age 4-5, whilst magnitude emerged as an important predictor 1 year later. In the current study, symbolic and non-symbolic magnitude correlated with maths, but it was only ordinal measures (Number ordering and Order WM) which explained variance in older children's maths ability, suggesting that magnitude-processing skills do not explain any additional variance other than the variance explained by Intelligence, Number line estimation, and both numerical and non-numerical ordering skills. These results support the prediction made in the previous chapter that Number ordering skills would become increasingly important to numerical development amongst older children, supporting the findings of previous research which has found similar results (Attout et al., 2014; Attout & Majerus, 2018; Lyons et al., 2014; Sasanguie & Vos, 2018). For children who have had at least four years' experience of formal schooling, it appears that ordinal strategies may overshadow magnitude-based strategies in terms of how children solve mathematical problems, which is consistent with the claim of Nieder (2009), who argued that children may first rely upon magnitude information in the early years of maths learning, but that as they develop, children rely more on their understanding of the relationship between numbers in solving problems.

Although magnitude-processing skills explained variance in maths achievement at age 5-6, after this period (and possibly when children may begin to automatize the number system), numerical ordering skills become more important to maths than magnitude-processing skills, as shown in the current study. This proposal is supported by the descriptive statistics shown in Table 3.1 (for Study 1) and Table 4.1 (for Study 2). Children's accuracy in the Number ordering task at age 5-6 was 76% and their reaction time for correctly-answered trials was just over 4 seconds. In study 2, the youngest children (8-9-year-olds) had an accuracy of 87% and their reaction times were over a second quicker in comparison to the children in Study 1. The oldest children's performance on the task was 95% and their reaction times were just over 2 seconds. These results suggest that by the age of 8, children's numerical performance would suggest that they had achieved a reasonable amount of mastery of the relationships between numbers in the symbolic number system.

Whilst symbolic and non-symbolic magnitude skills were related to maths achievement, these factors did not explain additional variance in children's maths achievement. This result was surprising, especially given the evidence in support of the role of symbolic comparison skills in numerical development across childhood (e.g. Fazio et al., 2014; Schneider et al., 2016). Whilst Lyons et al. (2014) found that Number comparison was the strongest of all predictors amongst children aged 8, the predictive power of this task appeared to decrease with age, which perhaps suggests why this task was not found to be a significant predictor. Nonetheless, the current study is more rigorous than the Lyons et al. study, given that the effect of several covariates were controlled for in the analysis. Furthermore, a curriculum-based maths assessment was used in the current study, whereas Lyons et al. only measured children's arithmetical skills, which is only one aspect of maths abilities. Additionally, performance on the measures in the current study was not only related to overall maths scores, but each individual maths skill that was measured by a curriculum-based test. Notably, each of these tasks has an ordering component.

Furthermore, the version of the task used by Lyons et al. involved both single-digit and double-digit trials, which may make the interpretation of the differences between the two tasks difficult. Nonetheless, it was evident that on a comparison task involving only single digits, children's performance was not a significant predictor of maths achievement. Although correlated with maths achievement, the finding that Block comparison did not explain additional variance is in line with other studies which have claimed that, given the methodological issues surrounding this task, that is may not be an accurate measure of the ANS (see Chapter 1, section 1.2). The additional analysis on the Block comparison task showed that the correlation observed between task performance and maths achievement was driven by children's' performance on incongruent trials, but the finding that this relationship remained significant, even after controlling for inhibition skills, is contrary to Gilmore et al. (2013), suggesting that in the current study, the observed link between non-symbolic magnitude-processing skills and maths achievement is not necessarily due to individual differences in the ability to inhibit irrelevant information during task performance. However, Gilmore et al. used a wider range of dots (between 5 and 28) in their task, whilst ours ranged from 1-9 blocks which appeared on the screen, so it is possible that inhibition skills may be more important as the number of stimuli presented increases, although this point would warrant further investigation.

Whilst Number line performance was unrelated to maths achievement in Study 1, the results of the current study show that performance on this task was an important factor in maths achievement for older children, which is in support of previous research which has suggested that performance on this task is linked to numerical development (Berteletti, Lucangeli, Piazza, Dehaene & Zorzi, 2010; Booth and Siegler, 2008; Siegler & Booth, 2004; Schneider et al., 2018; Siegler and Ramani, 2009). Indeed, Number line performance explained additional variance in maths achievement, even after controlling for numerical and non-numerical ordering skills, which supports the proposal that the number sequence is represented along a mental number line, which may become more precise as children get older.

4.4.2 Numerical and non-numerical ordering skills were equally important to maths achievement

In line with the hypothesis stated earlier, both numerical and non-numerical ordering skills (Number ordering and Order WM) were predictive of 8-11 year old children's maths achievement, and the regression beta-weights showed that both of these skills were equally important to numerical development amongst older children. Whilst in Study 1, both of these measures were correlated with maths achievement at both time-points, for older children these measures explained variance in maths achievement, even after controlling for Number line estimation and intelligence. This finding supports the prediction from Study 1 that numerical ordering abilities may not be an important predictor of maths achievement until after the age of 6, which has been shown in previous research (Attout et al., 2014; Lyons et al., 2014; Sasanguie & Vos, 2018). Furthermore, the age comparisons also show that performance on this task shows age-related improvement, independent of socioeconomic status, suggesting that school experience helps numerical ordering abilities to develop, and are not determined necessarily by a child's family background.

Visuospatial WM did not correlate with maths in any of the analyses, which is surprising given the evidence in support of the involvement of visuospatial WM in both typical and atypical maths development (e.g., Friso-van den Bos et al., 2013; Mammarella, Lucangelli & Cornoldi, 2010; Mammarella et al., 2015; Passolunghi & Mammarella, 2010, 2011; Passolunghi & Cornoldi, 2008; Peng et al., 2016; Szűcs et al., 2013). However, as mentioned in Chapter 1, visuo-spatial skills may be more important to maths development in younger children, whilst verbal skills may play a more significant role in numerical development for older children. Although it may also be the case that the maths assessment did not contain enough items which would involve children having to tap into their visuo-spatial skills in order to arrive at a correct solution.

Ordering skills involving the retrieval of familiar sequences from long-term memory did not appear to be related to mathematical development amongst older children. Performance on the Annual event ordering task, and OPQ scores were unrelated to maths achievement, which is in stark contrast to the finding that these skills in Study 1 were an important factor in children's initial numerical development. This suggests that these skills have much more of an influence on numerical development in the early years, whereas for older children, they may rely more on the retrieval of the order of the number system from long-term memory, as they would have learned to automatize the number system by this stage of development.

4.4.3 What is the relationship between ordering measures (and between ordinal and magnitude measures) in older children?[9]

As previously mentioned, the analysis of the correlations between the tasks in Study 1 showed that; 1) numerical and non-numerical ordering measures were correlated at both time points; 2) magnitude tasks correlated with numerical and non-numerical ordering measures at both time points, and 3) magnitude measures were unrelated to each other at both time points.

In the current study, the numerical and non-numerical ordering tasks were correlated to a far lesser extent than in Study 1, given that the only significant relationship was found between Number ordering and Annual events performance. The only non-numerical ordering measures which correlated with each other were Visuo-spatial WM and Annual events. As was found in Study 1, the magnitude measures correlated with both numerical and non-numerical ordering tasks; both symbolic and non-

[9] Correlations between each of the measures that were used in Study 1 and 2 are outlined in Chapter 5

symbolic magnitude tasks were correlated with Order WM, Number ordering and Annual events performance. This is in accordance with Lyons et al. (2014), who also found a significant correlation between Number ordering and both symbolic and non-symbolic magnitude (Dot comparison and Number comparison tasks). Number comparison was also related to Visuo-spatial WM, whilst Block comparison was correlated with OPQ scores.

As was the case in Study 1 (at both time-points), symbolic and non-symbolic magnitude measures were unrelated to each other. Although both studies differed in terms of the type of ANS task used, and in terms of the format of the Number comparison task used in each, this finding is nonetheless in contrast with the literature regarding a link between symbolic and non-symbolic magnitude-processing skills and maths amongst children (e.g., Chen & Li, 2014; Fazio, Bailey, Thompson & Siegler, 2014; Schneider et al., 2016). Furthermore, the lack of a significant correlation between the measures was not due to the different ways in which performance on these measures was indexed (Number comparison performance was measured using combined accuracy and reaction times, whilst Block comparison was measured using accuracy), as the correlation between accuracy on Number and Block comparison was small, negative and non-significant (r = -.04). The evidence presented in both studies provides support for the argument that the systems responsible for processing symbolic and non-symbolic magnitude are unrelated, suggesting that the ANS is not necessarily the precursor to the development of symbolic number knowledge, either in early or later childhood.

4.4.4 Reading skills were significantly predicted by non-numerical ordering skills (Order WM and OPQ score)

A final issue concerns the relationship between the measures and reading abilities. One proposal (e.g., Perez, Majerus and Poncelet, 2012, 2013) is that individual differences in order-processing skills may underlie the difficulties that some children have with reading and mathematics (at least this could be one reason why these conditions quite often co-occur). In the current study, after controlling for the covariates, only ordinal measures (OPQ, Order WM and Number ordering) were significantly correlated with reading, suggesting that those children who have better ordering skills also tend to have stronger reading skills. The regression analysis revealed that both Order WM and OPQ scores explained variance in children's reading scores, even after controlling for Vocabulary knowledge. This suggests that non-numerical ordering skills are somewhat involved in the development of reading skills, which is not solely explained by children's knowledge of the meaning of words. Despite this finding, much more research is needed to investigate the nature of this relationship, as well as whether deficits in order-processing skills may be one of the features of reading difficulties (e.g. Perez, Majerus & Poncelet; 2012, 2013).

4.4.5 Domain-general factors (except for socioeconomic status) were found to be related to maths achievement

As predicted in the previous chapter, Intelligence was found to be even more strongly related to maths achievement amongst older children than for younger children, and even explained variance in children's maths (and reading) scores. Given that intelligence skills measured in childhood is a strong predictor of future socioeconomic outcomes (e.g. Deary, Strand, Smith & Fernandes, 2007; Strenze, 2007), this perhaps explains why intelligence skills become increasingly important to mathematical achievement as children develop.

The finding that socioeconomic status was unrelated to maths development amongst older children is in contrast to Sirin (2005), although this is possibly due to cultural differences between the current study and Sirin's meta-analysis. It may have also been possibly due to differences between Study 1 and Study 2 in how socioeconomic status was measures (see Chapter 5). Nonetheless, although higher levels of deprivation were found amongst older children, the age effects in these cognitive tasks suggests that performance on numerical and non-numerical measures are relatively independent of children's family background, which suggests that these skills are not affected by a child's relative level of deprivation.

Response inhibition, as measured by the Stop-signal task, was found to be robustly related to maths achievement, which supports previous research which has found a link between inhibition skills and maths (e.g. Friso-van den Bos et al., 2013; Jacob & Parkinson, 2014), although it did not explain additional variance in children's maths achievement, suggesting that inhibition skills are less important in numerical development amongst older children, when compared to skills such as numerical ordering or estimation.

Chapter 5: Discussion

5.1 Summary of experimental studies

The findings from the experimental studies show that order-processing skills play an important role in the development of maths skills throughout the primary school years. The following subsections outline some of the key highlights of the experimental studies.

5.1.1 Findings related to ordering skills

- Both numerical and non-numerical order-processing measures correlated with maths achievement in the first two years of primary school
- The ability to process order for familiar events and for familiar everyday tasks was longitudinally predictive of maths achievement over 1 year later, even after controlling for Counting skills
- The ability to process order for familiar everyday tasks predicted growth in maths skills between children's first and second years of primary school, even after controlling for non-symbolic magnitude skills
- Ordering skills involving the retrieval of familiar numerical sequences from long-term memory and the retrieval of novel, non-numerical sequences form short-term memory correlated with maths achievement amongst older children. These skills also predicted maths ability, even when controlling for intelligence and number line performance
- Ordering skills involving the retrieval of novel, non-numerical

sequences from short term memory, and ordering skills involving the retrieval of familiar numerical sequences from long-term memory, also correlated with children's reading skills (as did the ability to process order for familiar everyday tasks also correlated with children's reading skills). The first two measures also explained variance in reading skills, even after controlling for Vocabulary knowledge (and Number line estimation).

5.1.2 Findings related to other skills

- Intelligence was related to maths achievement for both older and younger children (except for Block design at age 4-5-years-old), and explained variance in older children's maths achievement
- Socioeconomic deprivation was negatively correlated with maths achievement amongst young children, but uncorrelated with maths achievement amongst older children
- Performance on the Number line task was unrelated to maths achievement amongst younger children, but was significantly correlated with maths achievement for older children, and significantly explained variance in maths achievement
- Both symbolic and non-symbolic magnitude skills related to maths achievement for both older and younger children (except for Non-symbolic addition at age 4-5-years-old). These measures explained independent variance in maths achievement for 5-6-year-olds only.

5.2 How do the experimental studies help to answer the questions posed in this thesis?

In the following subsections, I will discuss the extent to which the findings from the experimental studies answer the questions outlined earlier in the thesis.

5.2.1 The role of the ANS in early numerical development

The first question concerned whether the ANS is strongly involved in the early development of mathematical skills. As shown in Table 5.1, no significant correlations were observed between symbolic and non-symbolic magnitude measures, supporting the assertion that the underlying mechanisms for the processing of symbolic and non-symbolic magnitude are unrelated (e.g., Holloway & Ansari, 2008; Maloney et al., 2010; Sasanguie, De Smedt, Defever & Reynvoet, 2012). This finding casts doubt upon the claim that the ANS is the intermediary step between approximate and exact numerical skills (e.g., Bonny & Lourenco, 2013; Halberda, Mazzocco & Feigenson, 2008; Halberda, Ly, Wilmer, Naiman & Germaine, 2012; Libertus, Feigenson & Halberda, 2011; Libertus, Odic & Halberda, 2012; Lourenco, Bonny, Fernandez & Rao, 2012; Mazzocco, Feigenson & Halberda, 2011; Mundy & Gilmore, 2009; Nosworthy, Bugden, Archibald, Evans & Ansari, 2013), and therefore may not be as important to the subsequent development of mathematical skills as was previously thought. Furthermore, as shown in Table 5.2, performance on the Non-symbolic addition task was unrelated to maths achievement at the end of children’s first year of primary school, but task performance did correlate with maths achievement for 5-6-year-olds and for 8-11-year-olds. Concerning the question posed by Chen and Li (2014) regarding the directionality of the relationship between the ANS and mathematical achievement, these results suggest that it is possible that ANS skills improve as a result of maths learning, rather than vice-versa.

Table 5.1. Table showing the correlations between symbolic and non-symbolic magnitude; correlations between non-symbolic magnitude and numerical ordering skills, and correlations between symbolic magnitude and numerical ordering skills

	Number comparison		
	4-5 y/o	**5-6 y/o**	**8-11 y/o**
Non-symbolic addition/ Block comparison	.15	.19	.14
	Number order		
	4-5 y/o	**5-6 y/o**	**8-11 y/o**
Non-symbolic addition/ Block comparison	.19	.36**	.31*
	Number order		
	4-5 y/o	**5-6 y/o**	**8-11 y/o**
Number comparison	.29**	.45**	.41**

* $p < .05$, ** $p < .01$

Table 5.2. Correlation coefficients between each measure and mathematical achievement in each age group

	4-5 y/o	**5-6 y/o**	**8-11 y/o**
Deprivation	-.29**	-.29**	-.11
Vocabulary	.32**	.37**	.48**
Block design	.16	.29**	.41**
OPQ	.30**	.28*	.15
Order WM	.32**	.23*	.48**
Daily/Annual events	.46**	.41**	.16
Number Order	.40**	.37**	.30**
Number comparison	.21*	.24*	.22*
Non-symbolic addition/comparison	.14	.30**	.27**
Number Line (error)	.02	-.17	-.35**

** $p < .05$, ** $p < .01$*

5.2.2 The role of domain-general factors in numerical development across childhood

As shown in Table 5.2, IQ measures showed age-related change in the strength of their relationship with maths. Amongst older children, intelligence measures significantly explained significant variance in maths achievement, even after controlling for numerical and non-numerical order-processing skills and Number line performance, suggesting that these skills are strongly linked to later numerical development even when considering the contribution of other skills that have been previously found to be important to numerical development.

As shown in Table 5.2, socioeconomic status was related to maths achievement for children aged between four and six (children from more deprived socioeconomic backgrounds tended to perform worse in maths, compared to children from less deprived socioeconomic backgrounds). However, this relationship was no longer significant for 8-11-year-olds, which suggests that perhaps the negative effects of socioeconomic deprivation may dissipate after a few years of school experience. The developmental trajectory of these domain-general measures will be discussed in further detail later in the chapter.

5.2.3 Are order-processing skills predictive of maths achievement across childhood?

The first question concerned whether order-processing skills were predictive of children's mathematical achievement. As shown in Table 5.2, both numerical and non-numerical order-processing measures were related to maths achievement for 4-6-year-olds, whilst Order WM and Number ordering were related to maths achievement amongst 8-11-year-olds. The concurrent regression analysis showed that performance on the Daily events and OPQ scores predicted maths achievement at the end of children's first year of school, even when controlling for Counting skills, suggesting that order-processing skills (of a non-numerical nature) are important in the early development of numerical abilities. Although Order-processing skills were related to maths achievement at the end of children's second year of primary school, they did not explain variance in maths achievement at this point, after considering the contribution of magnitude-processing skills to numerical development.

The longitudinal regression analysis showed that OPQ scores and Daily events performance at age 4-5 predicted variance in maths achievement at age 5-6, even when controlling for ANS skills and age. Children's maths achievement at the end of the Foundation years of school can therefore be predicted based on the extent to which they have developed adequate skills for processing the order of familiar content and retrieving the correct sequence from long-term memory, which suggests that perhaps these skills could be a suitable target for early intervention for children who show difficulties with maths learning in the early years of primary school. Furthermore, both Order WM and Number ordering skills predicted variance in maths achievement for 8-11-year-olds, even when controlling for intelligence and Number line performance, which suggests that, irrespective of whether the content is numerical or non-numerical, order-processing skills are also important in the development of mathematical skills amongst older children.

5.2.4 At what age do order-processing skills become important to maths development?

Regarding the issue of when ordinality becomes important to the development of maths skills, Sasanguie and Vos (2018) posed the question of whether non-numerical ordering abilities are related to maths achievement early in development, given the evidence of a link between non-numerical ordering skills and arithmetic in adults (Franklin, Jonides &

Smith, 2009; Morsanyi, O'Mahony & McCormack, 2018; Vos et al., 2018). The current results suggest that this is indeed the case. Study 1 is the first to show the importance of order-processing skills in such a young sample of school-age children; it appears that right from the outset of formal schooling, children's order-processing skills play a vital role in the development of numerical skills. Furthermore, these results show that order-processing skills are also important in numerical development amongst older children, as shown in Study 2, but it appears to be that there is a shift in terms of which types of ordering skills are important at each stage of development. For younger children, their early maths learning is supported by non-numerical ordering skills that involve familiar sequences. For older children, the importance of numerical ordering skills comes to the fore, which is consistent with other research suggesting that these skills emerge in terms of their importance to maths achievement after the age of six (Attout & Majerus, 2018; Lyons et al., 2014; Sasanguie & Vos, 2018), whilst WM skills involving the retention of order information are also important to the development of numerical abilities amongst older children.

5.2.5 Is the importance of order-processing skills to maths restricted to the ordering of numbers? Are order-processing skills restricted to the domain of maths or are they also important to reading?

In answer to the question of whether the importance of ordinality to maths is restricted to the domain of numbers, this does not appear to be the case, given that ordering skills for familiar events and for familiar everyday tasks seems to play an important role in supporting early numerical development, whilst ordering skills involving the retrieval of novel, non-numerical sequences from short-term memory are implicated in mathematical development amongst older children. As predicted, numerical ordering emerged as a significant predictor of maths achievement amongst 8-11-year-olds, although numerical ordering skills were related to maths across development, suggesting they were an important factor for the development of numerical abilities throughout childhood.

It appears that ordering skills may also be involved in reading development, given that both OPQ scores and Order WM also explained significant variance in reading scores, even after controlling for Vocabulary scores, indicating that the influence of ordering skills is also apparent amongst older children, for both reading and mathematical skills, and shows that the importance of ordering skills is not solely restricted to the development of numerical skills during the school years.

5.2.6 Are order-processing skills more important to mathematical development than magnitude skills?

Another question concerned whether ordinality is more important to numerical development than magnitude. To a certain degree, this appears to be the case. For 4-5-year-olds, although symbolic magnitude was an important factor in early numerical development (see Table 5.2), it did not predict additional variance in maths achievement, once the contribution of non-numerical order-processing skills and Counting skills had been accounted for, suggesting that these non-numerical ordering skills contribute more to early mathematical development than numerical comparison skills.

For 5-6-year-olds, only the magnitude measures (and Counting skills) explained variance in maths achievement, suggesting that magnitude-based strategies for solving maths problems become more apparent at this age, possibly as a consequence of children's experience of learning maths in a formal setting (especially since these measures are mathematical-related).

In the longitudinal analysis, both non-symbolic magnitude measures (Non-symbolic addition) and non-numerical order-processing measures (OPQ and Daily events) at age 4-5 explained variance in maths scores at age 5-6, and both OPQ scores and Non-symbolic addition also explained growth in maths skills over the same period, suggesting that both measures may be useful early predictors of children's mathematical success at the end of children's Foundation years of primary school, and may be suitable targets to identify children with weaknesses in maths learning, and to base interventions upon aimed at improving maths skills amongst these children.

5.2.7 How are ordinal and magnitude measures related to each other?

A final question concerned the relationships between ordinal tasks, and between both ordinal and magnitude tasks. Regarding the link between numerical ordering skills and magnitude-processing skills, as shown in Table 5.1, non-symbolic magnitude-processing skills were related to Number ordering skills for 5-6-year- olds and for 8-11-year-olds, but not for the youngest children, which is perhaps not surprising given that non-symbolic magnitude was also unrelated to maths achievement for the youngest children, whilst Number ordering was related to maths achievement for that age group. Nonetheless, this result shows that the ANS may be involved in the development of numerical ordering abilities from the age of 5 onwards. Number ordering and comparison skills were correlated for all age groups, which is consistent with previous research (Attout & Majerus, 2018; Attout et al., 2014; Lyons et al., 2014; Sasanguie & Vos, 2018) and suggests that there is a common mechanism for the processing of magnitude and ordinality with respect to numerical information.

Regarding the correlations between non-numerical ordering skills and magnitude-processing skills, Table 5.3 Shows that Number comparison performance was related to Order WM across all age groups which is in contrast to other studies with both older and younger children (Attout et al., 2014; Morsanyi, van Bers, O'Connor & McCormack, 2018). Number comparison performance was also related to temporal ordering skills across all age groups, which suggests that comparison skills may be somewhat involved in the performance of temporal ordering tasks. Number comparison was unrelated to OPQ scores. Non-symbolic addition performance was related to all non-numerical order-processing measures for 8-11-year-olds, but was only related to Order WM for 5-6-year-olds and only related to Daily events performance for 4-5-year-olds. This suggests that the ANS may be, to some extent, a building block of general ordering skills across development.

Number ordering correlated with Order WM for 4-5-year-olds and for 5-6-year-olds, but not for 8-11-year-olds, which is in contrast to our prediction and with previous studies (Attout & Majerus, 2018; Attout et al., 2014). However, both tasks explained variance in maths achievement for the oldest group, which suggests that these measures contribute differently to the development of numerical abilities amongst older children. Number ordering skills were correlated with temporal ordering skills (Daily and Annual events tasks) in all age groups, supporting the proposal made in Chapter 2 that numerical and temporal ordering skills are related. OPQ scores only correlated with Number order for 4-5-year-olds. These results are somewhat consistent with neuropsychological studies which have found evidence of common mechanisms responsible for the processing of numerical and non-numerical order (e.g. Fias, Lammertyn, Caessens & Orban, 2007; Fulbright et al., 2003; Ischebeck et al., 2008; Kaufman et al., 2009).

Concerning the correlation between non-numerical ordering tasks (see Table 5.4), as mentioned previously, these links have not been investigated in the case of young children. Consistent with previous research with older children (Morsanyi, van Bers, O'Connor & McCormack, 2018), OPQ scores were unrelated to any of the other non-numerical ordering measures. Whilst it was predicted that OPQ scores and temporal ordering performance would be correlated, there were weak, non-significant correlations between the two, suggesting that these tasks tap different aspects of order-processing, even though both involve the retrieval of familiar sequences from long-term memory. The only significant correlation between non-numerical ordering measures was found between Daily events and Order WM performance for 4-5-year-olds. Given that non-numerical ordering measures correlated with Number ordering performance across age groups, this suggests that these tasks share a common order-processing mechanism. However, the lack of consistent correlations between these non-numerical measures may suggest that they are measuring different aspects of order-processing.

Table 5.3. Table showing the correlations between non-numerical ordering skills and non-symbolic magnitude, symbolic magnitude, number line estimation and numerical ordering skills

	Non-symbolic addition /Block comparison		
Predictor	**4-5 y/o**	**5-6 y/o**	**8-11 y/o**
OPQ	-.14	-	.22*
Order WM	.11	.25*	.22*
Visuo-spatial WM	-	-	.02
Daily/Annual events	.22*	.11	.20*
	Number comparison		
Predictor	**4-5 y/o**	**5-6 y/o**	**8-11 y/o**
OPQ	.20	-	.02
Order WM	.28**	.37**	.22*
Visuo-spatial WM	-	-	.22*
Daily/Annual events	.34**	.36**	.34**
	Number order		
Predictor	**4-5 y/o**	**5-6 y/o**	**8-11 y/o**
OPQ	.26*	-	-.03
Order WM	.41**	.45**	.15
Visuo-spatial WM	-	-	.17
Daily/Annual events	.24*	.33**	.60**

* $p < .05$, ** $p < .01$

Table 5.4. Table showing the correlations between non-numerical ordering measures

	Order WM		
Predictor	**4-5 years old**	**5-6 years old**	**8-11 years old**
OPQ	.18	-	.06
Daily/Annual events	.44**	.15	.12
Visuo-spatial WM	-	-	.01
	OPQ		
Predictor	**4-5 years old**	**5-6 years old**	**8-11 years old**
Daily/Annual events	-.08	-	.05
Visuo-spatial WM	-	-	.12

5.3 Implications arising from the results of the thesis

The results of this thesis are a useful contribution to our understanding of the development of mathematical skills, and have built upon the existing literature concerning how order-processing abilities are important in numerical development. In the following subsections, I will outline the contributions of this thesis to the field of mathematical cognition research, as well as both the practical and theoretical implications of the findings. I will also discuss to what extent the measures changed in terms of their relationship with maths across development; which results that I found were unexpected in both studies, as well as predicting which results one may expect to see for the age group which wasn't tested in the current thesis.

5.3.1 How does the role of magnitude, ordinal and general measures in numerical development change across development?

In the following subsections, I will discuss the extent to which the skills measured in this thesis change in terms of their relationship with maths across development.

5.3.1.1 Socioeconomic status

The results of the current study show the opposite pattern to that of Sirin (2005), as socioeconomic status appeared to have a stronger effect on maths learning for younger children (as shown in Table 5.1), but there was no evidence of the same effect for older children. Given the evidence which suggests that poor numeracy (and literacy) skills are linked to negative socioeconomic outcomes (Department for Employment and Learning in Northern Ireland, 2013; Northern Ireland Audit Office, 2009), this would suggest that parents of young children from low socioeconomic backgrounds may themselves have relatively poor numeracy skills, and as a result, perhaps do not engage in as much maths-related activity with their children in the home environment. The upshot of this finding is that children from low socioeconomic backgrounds may need additional help with maths learning during the early years of schooling, as these are the foundation years upon which much of children's early maths learning is built. If children do not engage in much maths-related activity in the home, it could be the case that these children may struggle with early maths learning when they begin formal schooling.

It appears that by the time that children have had a few years' experience of schooling, the effect of their socioeconomic background on their maths learning ability appears to dissipate. However, it should be noted that socioeconomic status (measured by the NIMDM) was captured using the postcode of the child's school, rather than their own postcode. There were several children in the Study 2 sample who came from schools in rural areas, in which the postcode for their school would likely be the same as their own, therefore their deprivation scores would have been the same.

Also, Sirin (2005) found smaller effect sizes for the relationship between socioeconomic status and math achievement for children attending schools in rural areas (compared to children in urban and suburban areas), suggesting that this factor plays a less important role in numerical development for children living in less urbanized areas. Whilst the evidence from the thesis suggests that socioeconomic status may not be an important concurrent factor in later mathematical development, in a follow-up of Study 1 (O'Connor, Morsanyi & McCormack, in preparation), socioeconomic background at school entry significantly predicted maths achievement over three years later, when the same children were aged between 7-8 (see Appendix I), suggesting that socioeconomic status does have some predictive power in identifying children who may be at risk of struggling with mathematics in Key Stage 1.

5.3.1.2 Verbal and non-verbal intelligence

The current data suggests that verbal and non-verbal intelligence play an important role in maths development, a finding which agrees with the findings of other authors (e.g. Roth et al., 2015; Yeniad et al., 2013). It appears that the importance of intelligence to mathematical development increases across development. In fact, in the follow-up of Study 1 (O'Connor, Morsanyi & McCormack, in preparation), the importance of these factors becomes even stronger when the same children were aged between 7-8 (see Appendix I), as these skills are shown to be the strongest longitudinal predictors of maths over three years later, which shows the increasing importance of intelligence to the development of maths skills throughout the primary school years.

Why does intelligence become increasingly important to maths across development? It could be the case that the underlying skills tapping both subtests used may play a role in children's mastery of increasingly complex mathematical problems. Children with a better grasp of vocabulary knowledge may be better at solving mathematical word problems, as these involve knowing how to process the verbal content of these problems effectively to arrive at the correct solution. The importance of spatial reasoning skills (as measured by the Block design subtest) to maths may be due to children having to solve problems which involve the processing of spatial relationships, such as geometric problems, assessing whether shapes have a line of symmetry, or solving problems involving co-ordinates). Children who have a better grasp of vocabulary and spatial reasoning skills may be more likely to correctly solve mathematical problems which relate to these maths-related skills, and since these maths-related skills increase in complexity across primary school, those children who possess higher intelligence are more likely to perform better on standardized mathematical assessments, compared to children with lower intellectual abilities. Given that children's intelligence is measured yearly from their third year of primary school (Council for the Curriculum, Examinations and Assessment, 2007), it may be important for schools to monitor the progress of children who score low on these assessments, as it is likely that these children will also perform poorly in other academic subjects.

5.3.1.3 Ordinal measures

All of the ordering tasks were related to maths for young children, suggesting that these skills are important in early maths learning. The OPQ and Daily events tasks predicted variance in children's maths scores at the end of children's first year of primary school, as well as longitudinally predicting maths achievement 1 year later, suggesting that it is these skills in particular which may strongly contribute to the early development of numerical abilities.

Order-processing skills involving the retrieval of the number sequence from long-term memory, as well as the retrieval of novel sequences, appeared to play an important role in the development of mathematical abilities amongst older children. As proposed by Attout et al. (2014), serial order working memory skills involve both serial storage and serial rehearsal processes, the latter becoming important at a later developmental stage. For older children, they may be more likely to utilize sub-vocal rehearsal strategies to aid their mathematical performance, which younger children are perhaps not as adept at utilizing.

5.3.1.4 Magnitude and estimation measures

Across development, both symbolic and non-symbolic magnitude-processing skills were related to the development of maths skills (except for Non-symbolic addition at T1). Symbolic and non-symbolic magnitude-processing skills explained variance in maths achievement for 5- 6-year-olds, a finding which is consistent with Sasanguie and Vos (2018), who found the importance of Number comparison skills amongst children of the same age. Sasanguie and Vos also found that magnitude-processing skills emerged before order-processing skills, consistent with previous research (e.g. Colomé & Nöel, 2012; Wiese, 2007; Vogel et al., 2015). Given that non-symbolic magnitude-processing skills were uncorrelated with maths achievement at the beginning of primary school, this suggests that perhaps the ANS does not play as important a role in early numerical development as first thought (see section 5.3.4 for further discussion).

For older children, symbolic and non-symbolic magnitude skills were also related to maths achievement, suggesting that they were involved in numerical development at this stage. As proposed earlier, this may be due to children's experience of formal maths learning having the effect of improving these skills, rather than vice-versa. Magnitude skills did not explain variance in maths achievement, after considering the contribution of other numerical and non-numerical factors, suggesting that these skills did not contribute to older children's maths development, over and above the contribution of order-processing and estimation skills.

If much of maths learning in school involves the processing of Arabic symbols, why did Number comparison performance not become increasingly important to maths, in the same way that Number ordering did? This can be answered in terms of how number ordering and comparison skills relate to the underlying knowledge that children use in solving mathematical problems.

Miller and Hudson (2007) distinguished between three types of knowledge that underlie much of maths learning; conceptual knowledge (interpreting and understanding mathematical concepts), procedural knowledge (following procedures in mathematical operations) and declarative knowledge (retrieval of mathematical information from long-term memory), which may be important to maths learning at different stages of development. Sasanguie and Vos (2018) suggest that children in grade 1 (between 5-6 years-old) solve arithmetical problems by utilizing procedural knowledge. When children then begin to learn about multiplication from around 6-7 years old, this facilitates a shift towards a reliance on declarative knowledge, which children can then use to apply to other arithmetical problems as well. Sasanguie and Vos propose that Number comparison relies on conceptual and procedural knowledge (being able to identify the quantity that the number represents and comparing it with another number), whilst Number ordering may rely on declarative knowledge (the retrieval of the ordinal relations between the numbers in the number sequence from long-term memory).

Consistent with this assertion, the current results showed that Number comparison performance was found to be an important predictor of maths achievement for 5-6-year-olds, whilst Number ordering only emerged as a significant predictor amongst 8-11-year-olds, which supports the proposal of Nieder (2009), who argued that eventually, ordinal information about the number system eventually becomes more important to maths learning than information about the magnitude of numbers, and this shift seems to occur at an early age.

Number line estimation was a poor predictor of academic achievement during children's first year of school (see section 5.3.3 for an explanation), although from then onwards, it appeared that the relationship between task performance and maths achievement increased steadily, until it became an important factor in later maths development for older children, more so than either symbolic or non-symbolic magnitude measures, supporting the assertion that estimation skills play an important role in maths development (Schneider et al., 2018; Schneider, Thompson & Rittle-Johnston, 2018). These results are consistent with those of Schneider, Thompson and Rittle-Johnston (2018), who found that for children over the age of 6, Number line estimation was a stronger predictor of maths achievement than Number comparison performance, which did not predict variance in maths achievement for older children. Given that this task is proposed to tap the representation of the order of numbers along a mental number line (e.g., Bonato, Zorzi, & Umiltà, 2012; Kaufman, Vogel, Starke, Kremser, & Schocke, 2009; Link, Huber, Nuerk & Moeller, 2014; Moyer & Landauer, 1967), and that it predicted variance in maths achievement along with Order WM and Number ordering, this would suggest that it is the ordinal nature of this task that explains why estimation skills are important to maths; those children who were more effective at retrieving the order of numbers from the mental number line, would perform better in standardized maths assessments, compared to children with less efficient retrieval of the number sequence.

5.3.1.5 A cautionary note regarding the interpretation of developmental trends

Whilst the results of this thesis offer some insight into the development of magnitude, ordinal and general skills during the primary school years, it should be noted that (1) Study 2 was not a longitudinal study, therefore one must be careful in interpreting the development of these skills across the age groups, as the lack of a longitudinal design in Study 2 makes it difficult to distinguish whether developmental changes in certain skills can be attributed to the development of the underlying representations that drive these skills, or whether developmental changes in task performance simply arise as the result of individual differences in task performance. Nonetheless, the results do indeed show patterns of development in ordinal, magnitude and intellectual skills that would largely be expected, despite the disparity in the sample size of each group, and also in spite of the finding that older children in Study 2 came from areas with higher deprivation than younger children in the same study. Had Study 2 been a longitudinal study, which tracked the same sample of children through the last three years of primary school, then this would have allowed for much stronger conclusions to be made regarding the development of ordinal, magnitude and intellectual skills in the latter years of primary school, although this would have been beyond the scope of this thesis. Nonetheless, more longitudinal work is needed in order to investigate the developmental trends of numerical and non-numerical ordering skills, amongst children who have had some experience of formal education (e.g. children in their third year of primary school and beyond).

5.3.2 What new ideas/findings can the current work contribute to the field?

This thesis is the first to show that non-numerical order-processing skills, involving the retrieval of the sequence of familiar events (Daily events task), and the retrieval of a sequence of familiar everyday tasks (OPQ), are strongly involved in early numerical development. Furthermore, many other studies have focused on the importance of order-processing skills for performing arithmetic (e.g. Attout & Majerus, 2015, 2018; Attout et al., 2014; Lyons et al., 2014; Sasanguie & Vos, 2018). However, the results of the thesis also show that these ordering skills are related to many aspects of the mathematical curriculum in Northern Ireland, rather than being related to just one aspect of mathematical learning. Whilst it has been proposed by some authors that children acquire knowledge of the magnitude of numbers earlier than they acquire ordinal knowledge (e.g. Colomé & Nöel, 2012; Wiese, 2007; Vogel et al., 2015), the current results suggest that this is not necessarily the case, as Number ordering was also related to maths at both time-points for younger children. However, Number ordering performance did not explain variance in early maths skills, over and above that explained by these non-numerical ordering tasks (and counting ability).

These findings with young children have given a new insight into exactly which skills are important for early maths learning, as well as highlighting which types of skills may be suitable for early intervention.

The longitudinal analysis showed that order-processing skills for familiar events and for familiar tasks were predictive of maths achievement at the end of children's second year of school, even when controlling for Counting skills. This suggests that these types of ordering skills contribute to the development of numerical abilities, even when considering the contribution of children's early ability to recite the numbers in the correct order. This suggests that mathematical development in the early years is supported not only by the extent to which children are able to successfully enumerate the count list, but is also supported by more general ordering skills which, similar to counting, also involve the retrieval of a familiar sequence from long-term memory.

How exactly do these skills involving the retrieval of familiar sequences from long-term memory support early numerical development? During the first two years of formal schooling, children are only beginning to learn about the number sequence (Council for the Curriculum, Examinations and Assessment, 2007). Therefore, it is plausible to hypothesize that if children are not entering primary school with an adequate knowledge of the symbolic number system, then their learning of the numbers must be supported by other skills, which I earlier proposed were the ordering skills for familiar content. These ordering skills enable children to learn the correct order of items within a sequence, which enables these items to become more familiar. As a result, these skills may be considered to be important to numerical development, because it is via these general ordering skills that children can begin to learn the order of the number system. Those children who show better mastery of these ordering skills will consequently be more familiar with the order of the number system, compared to those children who have less efficient general ordering skills.

Even from a young age, children acquire mental representations of repeated sequences of events over multiple time scales during the early years (Fivush & Hammond, 1990; Nelson, 1986, 1998), and children as young as 4 years old have spatialized representations of the order of familiar daily events (Friedman, 1977; 1990). The retrieval of familiar content (such as a sequence of events or a sequence of everyday tasks) may involve the mental representation of a sequence, ordered from left to right, in a similar fashion to the proposed mental representation of number along a mental number line, suggesting an overlap between spatial, temporal and numerical order (Walsh, 2003; but see Tillman, Tulagan, & Barner, 2015). Indeed, there is increasing evidence which suggests that there is a link between temporal and numerical processing more generally (e.g. Ben-Meir, Ganor-Stern & Tzelgov, 2012, 2017; Bonato, Saj & Vuillermier, 2016; Casarotti, Michielin, Zorzi & Umiltà, 2007; Hubbard et al., 2005; Oliveri et al., 2008; Schwarz & Eiselt, 2009; Skagerlund & Träff, 2016). However, recent evidence also has proposed a specific link between the ability to process order for both numerical and temporal information (e.g. Magnani & Musetti, 2017; Ganor-Stern, 2015). Friedman and Brudos argue that 4-year-olds utilize a common mechanism for the coding of both spatial and temporal information, which suggests that this common representational format is activated during mathematical performance, which is consistent with the claim that temporal and numerical order are represented via a mental number line (e.g. Bonato, Zorzi, & Umiltà, 2012). Therefore, this suggests that young children's ability to process temporal order (in the case of the order of familiar daily events and for familiar everyday tasks) is supportive of their acquisition of symbolic number knowledge, and therefore plays a vital role in the mastery of early numerical skills.

Finally, another important finding concerned the stability of ordinal and magnitude measures during the first two years of school. As outlined in section 3.4.4, and in my recent work (see Appendix S), magnitude measures were shown to be weak or non-significantly correlated at both time-points, suggesting that these skills are undergoing a period of development during the first two years of school. On the other hand, non-numerical ordinal measures were significantly correlated at both time-points, suggesting that these skills could be considered as good candidate skills upon which early mathematical knowledge may be built upon, because they are already established at the beginning of formal education.

5.3.3 Which skills might be important to maths achievement amongst children in Key Stage 1?

Some predictions about which skills would be important for maths learning in children aged 6-8 can be made based on the findings from this thesis (see section 5.4 for a discussion as to why this age group wasn't tested).

Based on the evidence discussed in section 5.3.1.1, it may be possible that the effect of socioeconomic status on maths learning would reduce further, perhaps becoming non-significant for 7-8-year-olds. I argued earlier that it appears that the effect of socioeconomic status on maths achievement appears to reduce across development, therefore I would expect that the relationship between the two would become weaker for children in Key Stage 1. However, the preliminary analysis predicting maths achievement at age 7-8 from the T1 measures (O'Connor, Morsanyi & McCormack, in preparation) suggests that socioeconomic status longitudinally exerts an influence over later maths achievement. Nonetheless, I would predict that at the cross-sectional level, socioeconomic status would not be as strongly related to maths as previously found with younger children.

In contrast to socioeconomic status, I would predict that both measures of Intelligence measures would become even more strongly related to maths compared to the results of Study 1, perhaps even predicting variance in maths scores for children in Key Stage 1. This is based on the finding from our preliminary analysis of the follow-up data from the longitudinal data (O'Connor, Morsanyi & McCormack, in preparation) which suggests that intelligence measures at age 4-5 were more strongly related to maths three years later than any of the ordinal or magnitude measures. Therefore, it is reasonable to assume that this relationship would be even stronger than what was observed for younger children in Study 1.

Regarding the ordinal measures, I would predict that the OPQ and Daily/Annual events measures, which tap ordering skills for familiar content, would show a weaker relationship with maths, as it appears that these ordering skills play a more important role in early numerical development. On the other hand, and consistent with other research, I would predict that Order WM and Number ordering skills would become even more strongly related to maths (Attout & Majerus, 2018; Attout et al., 2014; Lyons et al., 2014; Sasanguie & Vos, 2018), as children adopt different strategies for solving mathematical problems (see section 5.3.1.3), and given that Number ordering skills only appear to emerge in their importance from the age of 6.

Given that symbolic and non-symbolic magnitude tasks showed relatively similar correlations with maths achievement, both for 5-6-year-olds and for 8-11-year-olds, I would predict that similar results would be found for 6-8-year-olds. Whilst magnitude skills explained variance in 5-6-year-olds maths achievement, I would predict that this may also be the case for 6-8-year-olds, but that I would also expect that if this were the case, they would begin to explain less variance in maths achievement than the Order WM and Number ordering measures, which I predict would come to the forefront as the most important predictors from the age of 6 onwards.

Finally, I would predict that the importance of Number line estimation to maths achievement would be quite similar amongst 6-8-year-olds, given that there was a similar strength correlation between the two for 5-6-year-olds and for 8-11-year-olds. Lyons et al. (2014) found that performance on this task was one of the strongest predictors of arithmetic between the ages of 6-8, before its influence relatively reduced amongst older children. Given the issues with the version of the task used with younger children, and the finding that this measure explained variance in maths achievement for older children, I would also predict that it would be a significant predictor of maths achievement amongst children in key Stage 1.

5.3.4 Which results were unexpected?

Arguably the most unexpected result found in this thesis concerned the finding that Number comparison performance was only weakly related to maths in both studies, and only explained variance in maths achievement at one time-point, which was surprising given the wealth of research evidence supporting the role of Number comparison performance in mathematical development (e.g., Castronovo & Göbel, 2012; Durand, Hulme, Larkin & Snowling, 2005; Bugden & Ansari, 2011; De Smedt, Verschaffel & Ghesquière, 2009; Fazio et al., 2014; Kolkman, Kroesbergen & Leseman, 2013; Lonneman, Linkersdörfer, Hasselhorn & Lindberg, 2011; Mundy & Gilmore, 2009; Sasanguie, De Smedt, Defever & Reynvoet, 2012; Sasanguie, Göbel, Moll, Smets & Reynvoet, 2013; Sasanguie, Van den Bussche & Reynvoet, 2012; Schneider et al., 2016; Vanbinst, Ghesquière & De Smedt, 2012; Vogel et al., 2015, Xenidou-Dervou et al., 2017).

Given that children only learn about the numerical symbols formally when they begin primary school, one would expect that the extent to which children are able to identify and compare symbolic quantities represented by Arabic digits would be likely to predict how well they would perform in maths. Whilst performance on this task was related to maths achievement in all studies, it only explained variance in maths scores for 5-6-year-olds. According to Sasanguie and Vos (2018), it may be around this time that children begin to rely less on procedural knowledge (which the Number comparison task taps into) and more on declarative knowledge (which the Number order task taps into). This is also supported by Attout et al. (2014), who found that Number comparison skills were unrelated to arithmetic at each time-point in their study, amongst 5-8-year-old children.

One possibility is that comparison skills may be utilized in other ordinal tasks (e.g. temporal and number order), particularly on mixed-order trials. As proposed by Sasanguie and Vos (2018), the numerical distance effect commonly found for mixed-order trials may reflect the use of a comparison strategy (Sasanguie & Vos, 2018), as children compare each digit to its successor in order to arrive at the correct solution. This could also be the case in the Daily events task, which was constructed in a similar way to the number ordering task. Given that Number ordering explained variance in older children's maths achievement, and Daily events task performance explained variance in maths achievement for younger children, it may have been the case that comparison skills were already partly accounted for in these regression models, hence why Number comparison performance was not a significant predictor for 4-5-year-olds or for 8-11-year-olds.

Another unexpected result was that estimation skills did not play a significant role in early numerical development, although the developmental pattern showed an increase in the strength of the relationship between the first two years of primary school. Nonetheless, this result is in contrast with the research evidence that has found that performance on this task is related to mathematical achievement, even in children as young as 3 years old (Berteletti, Lucangeli, Piazza, Dehaene & Zorzi, 2010; Booth and Siegler, 2008; Siegler & Booth, 2004; Siegler and Ramani, 2009; Schneider et al., 2018; Schneider, Thompson & Rittle-Johnston, 2018). One possibility for this result may be due to methodological issues associated with the version of the task used with young children. Typically, in studies of Number line estimation, researchers have employed a pencil-and-paper version of the task. I used a touchscreen version, in which children had to use their finger to point and press a position on the number line where they believed a target number would go. One of the issues with this task is that young children may not have adequately developed fine-motor skills so that they could indicate exactly where they thought the target number would be located. Nonetheless, children's estimates were generally close to the target and the task correlated with performance on the Block design task, which supports the validity of the task. Also, reliability estimates were adequate for performance across both time-points.

5.3.5 Theoretical implications for the study of mathematical development

As previously mentioned, there is evidence to suggest that even very young have spatialized representations of the order of familiar daily events (Friedman, 1977; 1990). Since Friedman and Brudos (1988) argue that the coding of both spatial and temporal information utilizes common mechanisms, it could be suggested that the retrieval of the order of familiar temporal information may help to create a representational template upon which the order of numbers is built upon, which would take the form of a spatialized mental time line (Bonato, Zorzi, & Umiltà, 2012). This mental time line may initially provide a template for the representation of familiar content (such as children's representation of familiar sequences), but that when children begin to learn about the number system, they can then use this mental time line representation to create a representation of the order of the symbolic number system, thus facilitating the representation of number along a mental number line. In this way, the representation of each number may be linked to the representation of each item in a familiar sequence (e.g. the number '1' represents 'waking up', '2' represents 'getting dressed' etc.). Since the Daily events task can be solved in a similar way to the number ordering task, based on the replacement of the event represented by its ordinal position within the sequence of daily events, this suggests that one would expect that performance on these tasks would be linked, which indeed was the case in both studies (even for the relationship between the Annual events and Number ordering tasks). Therefore, I argue that the retrieval of familiar ordered content from long-term memory serves as a precursor to the acquisition of early symbolic knowledge.

The results also offer some insight into the theoretical discussion regarding the mental representation of ordered sequences. Whilst it has been hypothesized that there is a common representational system for space, time and number (e.g. Walsh, 2003), there is a wider theoretical debate regarding the exact nature of the representations of order for these types of items. Some argue that there is a domain-general representational format which is involved in the representation and processing of ordered information in long-term memory, based on the representation of a mental number line (e.g. Arend, Ashkenazi, Yuen, Ofir & Henik, 2017; Bonato, Zorzi, & Umiltà, 2012; Cheung & Lourenco, 2015; Crollen & Nöel, 2015; Crollen, Vanderclausen, Allaire, Pollaris & Nöel, 2016; Dehaene, Bossini & Giraux, 1993; Franklin & Jonides, 2009; Lonneman, Linkersdörfer, Nagler, Hasselhorn & Lindberg, 2013; Moyer & Landauer, 1967; Seno, Taya, Ito &

Sunaga, 2011), whilst other researchers argue that ordered sequences are temporarily activated in WM during task performance, in the form of a mental whiteboard, which allows items to be spatially-oriented from left-to-right in order to be manipulated (e.g. Abrahamse, Van Dijck & Fias, 2016, 2017; Abrahamse, Van Dijck, Majerus & Fias, 2014; Fias & Van Dijck, 2016; Ginsburg, Archambeau, Van Dijck, Chetail & Gevers, 2017; Ginsburg & Gevers, 2015; Van Dijck, Abrahamse, Acar, Ketels & Fias, 2014; Van Dijck, Abrahamse, Majerus & Fias, 2013: Van Dijck & Fias, 2011; Van Dijck, Gevers & Fias, 2009; Van Dijck, Ginsburg, Girelli & Gevers, 2013).

The theoretical stance of the current thesis is that both numerical and non-numerical sequences are mentally represented on a mental time/number line, from left to right. As mentioned in Chapters 1 and 2, (canonical and reverse) distance effects in ordinal and magnitude tasks, and ratio effects in magnitude tasks, provide evidence of the representation of numerical/non-numerical sequences along the proposed mental number line, as these effects reflect the difficulty in comparing items that are close together due to the increasing overlap between the representations of adjacent items. Detailed analysis of performance on the binary choice magnitude and ordinal tasks in both (the computerized Number ordering task, Daily and Annual event order, Number comparison and Non-symbolic addition/comparison tasks) are shown in Appendices J-P. These analyses showed evidence of distance and ratio effects amongst both young and old children in the study, and provides support for the representation of both numerical and non-numerical sequences along a mental number/time line.

However, these results may only apply to these tasks which involve the retrieval of familiar content from long-term memory, whereas the Order WM task involves the retrieval of a novel, unfamiliar sequence from short-term memory. Thus, a distinction can be made regarding the mental representation of ordered sequences based on a) the familiarity of the content, and b) whether the content is retrieved from long-term or short-term memory.

As outlined in Chapter 1, evidence for the role of the ANS in the early development of symbolic number knowledge, and subsequently the development of mathematical skills comes from studies which have investigated whether there is a link between performance on symbolic and non-symbolic magnitude tasks, and whether performance on these tasks show similar effects (e.g. distance or ratio effects). However, the evidence in support of a link between symbolic and non-symbolic magnitude is already far from convincing (e.g., Holloway & Ansari, 2008; Maloney et al., 2010; Sasanguie, De Smedt, Defever & Reynvoet, 2012).

The contribution of the current work concerning this point is that I found that symbolic and non-symbolic magnitude-processing skills were unrelated, amongst both younger and older children, therefore the current results do not support the existence of a link between the two types of processing. My results suggest that the underlying processing of symbolic and non-symbolic magnitude are unrelated, therefore it could be the case that the ANS may have nothing to do with the system for symbolic number processing and therefore, cannot be considered the sole precursor to the development of symbolic number knowledge. Chen and Li (2014) concluded from their meta-analysis that neither hypotheses regarding the directionality of the ANS-maths causal relationship could be ruled out; that maths skills develop through the strengthening of ANS acuity, or that the strengthening of ANS acuity occurs because of maths experience through schooling. If the former hypothesis was the case, the one would expect that non-symbolic magnitude-processing skills at the beginning of primary school would be related both to maths achievement, and to symbolic magnitude. However, neither hypothesised result was observed, and in fact, both symbolic and non-symbolic magnitude were only found to play an important role in maths development in children's second year of school, by which time children had engaged in maths learning for over a year, suggesting that perhaps it is more likely that the strengthening of ANS acuity in non-symbolic tasks occurs as the result of formal maths learning at school, which is further evidence against the assertion that the non-symbolic magnitude-processing skills are the most important of all the precursors of early maths learning.

5.3.6 Practical implications for the study of mathematical development

One of the main practical implications of the thesis concerns the evident difficulties with comparing studies across cultures, in which children begin school at different ages. Northern Ireland has the youngest school starting age of most countries in Europe (Eurydice at NFER, 2013), as children begin primary school on the first September after their 4th birthday. Skills such as working memory and intelligence are expected to show age-related improvement. However, one of the difficulties is that the effects of both age and school experience can have an effect on the development of performance on cognitive predictors of maths, and this can become complicated as there are differences between countries regarding school starting age, making comparison of children from the same school grade difficult, as they will differ on chronological age, even of the children are at the same stage of schooling. This thesis highlights that there should be a greater awareness of these differences in the literature when researchers are drawing conclusions about specific samples of children.

The OPQ was created for the sole purpose of this thesis and was shown to be an important early indicator of later mathematical performance. In accordance with clinical reports of Dyscalculia (National Centre for Learning Disabilities, 2007), children rated by their parents as having lower ordering skills at the beginning of primary school, may be at risk of developing difficulties with maths even at this early stage. This suggests that this questionnaire may be useful as an early diagnostic tool for detecting maths problems in children, prior to their engagement in formal maths learning. Following on from this point, the current results also suggest that mathematical interventions could potentially be targeted towards children from a young age, as even parental indicators could identify children who may potentially be at risk of falling behind in terms of their numerical development. Since the Daily events task was shown to be an important predictor of early success, an intervention based on temporal ordering may be a suitable intervention task for young children, as it is non-numerical in nature and may reduce any potential maths anxiety effects, given that maths anxiety is evident even in young children (Cargnetti, Tomasetto & Passolunghi, 2017; Hill et al., 2016). The temporal ordering task could involve an adaptive procedure, much like the one used in the Math Garden recovery program (Jansen et al., 2013), so that the difficulty level of the task would adjust based on the child's performance.

Despite the growing number of studies that have implicated ordering skills in maths development, there has been a lack of research into the efficacy of training these skills to improve older children's maths ability, given that it was a strong predictor of 8-11-year-old's maths achievement. Two studies (Park & Brannon; 2013, 2014) had a group of adults in their training studies engaging in a numerical ordering training program, which involved the presentation of a triad of numbers. Participants had to use a mouse to click the numbers until the triad was in the correct ascending or descending order. The results of both studies found that although both groups who engaged in number order training did show transfer effects to maths performance, they did not show as large an effect compared to a group who were trained on approximate arithmetic. However, one of the main caveats of using a Daily events-type intervention is that it is non-numerical in nature, so performance on this intervention could be compared to an equivalent numerical ordering intervention, in order to assess the efficacy of a non-numerical versus a numerical ordering intervention, especially given recent evidence which has shown the positive benefits of numerical ordinality training in improving numerical outcomes amongst young children (van Herwegen, Costa, Nicholson & Conlan, 2018; Xu & Lefevre, 2016).

5.4 Limitations of the current thesis

5.4.1 Not including children from Key Stage 1

In this thesis, I tested children in Foundation (Primary 1 and 2) and Key Stage 2 (Primary 5, 6 and 7), but did not test children in Key stage 1 (Primary 3 and 4). Nonetheless, the focus of this thesis was on the early years and the final years of schooling, so I decided to choose to test a cohort throughout their Foundation years of school, whilst with older children I focused on Key Stage 2, as this age range are preparing for their final few years in school, with the end goal of completing their school-entry exams (although this is not the case for all children in Northern Ireland). However, I do appreciate that the longitudinal study may have been even stronger had I also tested the children with the same cognitive measures in their third and fourth years of primary school. However, there are also practical difficulties with testing children at this age (e.g. preparing for religious ceremonies, the onset of formal testing at the end of Key Stage 1) which also may have made it difficult to complete testing with children at these ages.

5.4.2 Not considering other skills (e.g. phonological awareness)

I did not consider the role of other skills, such as phonological awareness (De Smedt, Taylor, Archibald & Ansari, 2010; Jordan & Wylie, 2010, 2015; Passolunghi & Lafranchi, 2012; Passolunghi, Mammarella & Altoè, 2008; Passolunghi, Vercelloni & Schadee, 2010; Träff, Desoete & Passolunghi, 2017; Wylie, Jordan & Mulhern, 2012), which may also be an important skill in the development of numerical abilities in childhood.

Phonological awareness is also an important skill which underlies the development of reading abilities (Melby-Lervåg, Lyster & Hulme, 2012), and given that I found that order-processing skills were related to reading abilities, it may be possible that there is also a link between phonological awareness and order-processing skills. It would also be reasonable to speculate that there should be a link between children's verbal counting ability and phonological awareness. Nevertheless, phonological awareness could also be assessed in the future to investigate which types of ordering skills it may be related to, as well as whether it is more strongly related to maths achievement than order-processing skills.

5.4.3 No baseline assessment of maths achievement for younger children

Another limitation that could be noted is that formal maths skills were not assessed at the start of the first school year. Indeed, although I used a broad range of tasks to measure basic maths abilities (including non-symbolic measures, counting skills, and measures that required the knowledge of symbolic numbers, such as the number line task, and the number ordering task), it is possible that children had already possessed some of the formal maths skills (e.g., addition and subtraction) that were assessed at the end of the first school year. Most children would have attended state-funded nurseries the year before their first year, i.e., at aged 3 to 4 years, due to universal free provision in the UK. Nurseries do not teach formal maths skills such as addition and subtraction, but perhaps some children had been taught these skills at home (although we note that at the start of the study the children were still very young with a mean age of less than 5 years). Thus, although the findings demonstrated that early, non-numerical ordering skills were strongly related to formal maths skills at the end of the first school year, it is unclear if early ordering abilities predicted growth in formal math abilities during the first school year.

5.4.4 Issues with the non-symbolic magnitude tasks

I did not include the Non-symbolic addition task in Study 2 and instead included a measure of Non-symbolic comparison, despite the methodological issues surrounding the use of the task, as mentioned in Chapter 1 (e.g., Price, Palmer, Battista & Ansari, 2012; Inglis & Gilmore, 2013, 2014; Maloney et al., 2010). However, I wanted to use the exact same trials for the symbolic and non-symbolic comparison tasks (in the same way that I used the same trials in both the Number order and Annual event order tasks), which would not have been possible had I have used the Non-symbolic addition task. I piloted the Non-symbolic addition task, in addition to the other research tasks, with a few children and found that the test sessions were far too excessive in their length, so I decided to remove the Non-symbolic addition task from the study and to keep the Block comparison task as the measure of non-symbolic magnitude. Finally, in Study 2, the Block comparison task was constructed in such a way that it did not record accurate reaction time data, so this data was not used in the analysis. Whilst this was not ideal (especially given that performance on the Number order, Annual event order and Number comparison tasks were indexed using a combined accuracy and reaction time measure), accuracy on the Block comparison task were robustly correlated with both maths and reading scores, even though children's performance was close to ceiling.

5.5 Ideas for future research

5.5.1 Meta-analysis of the role of order-processing skills in numerical development

Given that there is now a large amount of experimental studies into the role of order-processing to maths ability, a meta-analysis of studies of numerical and non-numerical ordering skills in relation to mathematical abilities, involving both children and adults, would allow for a fuller synthesis of the available literature on the topic. Whilst there is a review of the research on the topic (Lyons, Vogel & Ansari, 2016), a meta-analysis of the available evidence would build on this and would be useful for various reasons; a) the strength of the relationship between ordering and maths could be compared to the strength of the relationship between symbolic and non-symbolic comparison tasks, in both the developmental and adult literature, to fully ascertain whether ordering or magnitude-processing skills are more strongly related to maths across a large number of studies; b) given that the role of non-numerical ordering in maths has not received as much research attention as numerical ordering, a synthesis of the available studies which have included these types of tasks may alert researchers to use these tasks in future studies; c) there are many different versions of the number ordering task, which have involved altering the number of presented symbols (dyads versus triads), the number of digits (single digits, double digits or triple digits), how trials should be responded to (e.g. correct order or incorrect order, ascending or descending) and indexes of performance (accuracy, reaction time, distance effect); by analysing the effect sizes for each version of the task, it could be determined which factors are important to consider when designing future experiments using the number ordering task.

5.5.2 Validation of the OPQ as a diagnostic tool for detecting potential mathematical difficulties at an early age

I created the two versions of the OPQ to specifically measure children's ordering skills in everyday, familiar tasks. Both versions of the questionnaire have been published alongside research on ordering skills and maths, in which they have been shown to be important factors in typical and atypical mathematical development (Morsanyi, van Bers, O'Connor & McCormack, 2018; O'Connor, Morsanyi & McCormack, 2018a, see Appendix Q). My thesis provides the first evidence of a link between everyday ordering skills and maths achievement. As mentioned previously, this questionnaire could be a useful diagnostic tool in identifying children at risk of developing maths difficulties, even in their first year of primary school. Although the questionnaire showed good psychometric properties, further work would be needed to improve its psychometric properties, and its predictive value, even further. A validation study across a large pool of children would be useful in determining these properties for young children

5.5.3 Further investigating the role of order-processing skills in reading development

Given the high comorbidity between Dyscalculia and Dyslexia, and that children with sustained maths difficulties perform significantly worse in English than children with average maths skills and children with high maths skills (Morsanyi, van Bers, McCormack & McGourty, 2018), and the link between Dyscalculia and order-processing skills as measured by the OPQ and Order WM tasks (e.g., Morsanyi, van Bers, O'Connor & McCormack, 2018), it is possible that ordering skills may play a role in the development of reading skills. This assertion is supported by recent evidence suggesting that Order WM performance is predictive of reading development in young children (Martinez Perez, Majerus & Poncelet, 2012) and that adults with Dyslexia also show impaired Order WM performance (Martinez Perez, Majerus & Poncelet, 2013; but see Cowan et al., 2017).

Individuals with Dyslexia may also struggle with mathematical-related skills, such as the retrieval of arithmetical facts (Träff & Passolunghi, 2015). Further support comes from the findings of Study 2, as both Order WM performance and OPQ scores were found to be important to reading skills amongst older children, even after controlling for Vocabulary skills; the same tasks that predicted group membership in Morsanyi and colleagues' study, either being in the Dyscalculia group or the control group (Morsanyi, van Bers, O'Connor & McCormack, 2018). It appears that order-processing skills may be somewhat related to reading skills, in both typical and atypical populations. These links, whilst based on some evidence, need to be investigated further to elucidate exactly what is the nature of the relationship between Dyslexia, order-processing skills and academic achievement. To establish whether this is the case, it might be interesting to carry out a similar experiment to that of Study 1, by longitudinally investigating the role of order-processing-skills to the development of reading skills from the outset of formal schooling, to examine whether order-processing skills are also important to the development of other academic skills. Indeed, given that both reading and maths skills have been found to be strongly related in a recent meta-analysis (Singer & Strasser, 2017), and that order-processing skills have been shown in the current study to be predictive of maths, it may be plausible to suggest that perhaps the relationship between reading and maths may be mediated by order-processing skills. As shown in Study 2, the Order WM measure explained variance in both reading and maths, so this task may be a suitable candidate to test this mediation hypothesis.

5.5.4 Examining order-processing skills in other cognitive disorders (e.g. Gerstmann's syndrome)

Recent research has suggested that a core deficit of Developmental Dyscalculia may be impaired order-processing skills (e.g. Morsanyi, Devine, Nobes & Szűcs, 2013; Morsanyi, van Bers, O'Connor & McCormack, 2018; Rubinstein & Sury, 2011). However, there are other disorders in which mathematical difficulties have been observed as a core feature, such as in Gerstmann's syndrome; a neurological condition stemming from brain lesions to the parietal cortex, resulting in deficits in the ability to write, carrying out mathematical computations, problems with distinguishing between fingers on one's hand and spatial problems (e.g. Carlota, Di Pietro, Ptak, Poglia & Schnider, 2004; Turconi & Seron, 2002; Vallar, 2007). In a previous study (Turconi & Seron, 2002) a patient with Gerstmann's syndrome showed impaired order-processing skills (he could recite ordered sequences, but was impaired on judging which item came next or before in a sequence) for numbers, letters, days of the week and months of the year. On the other hand, his ability to process magnitude (measured by number and dot comparison-type tasks) showed a significant distance effect, suggesting his ability to process magnitude was spared. Despite being based on a single-case study, these results nonetheless suggest a disassociation between the mechanisms that process magnitude and ordinality. It would be interesting to investigate, with a larger sample of patients with Gerstmann's syndrome, whether these patients would exhibit deficits in the same kind of ordinal and magnitude tasks used in the current study, relative to matched controls, to further investigate the nature of the mathematical deficits exhibited in this disorder.

5.5.5 Examining the differences between high and low mathematics achievers

Another area of interest for future research could be to examine differences between high maths achievers, low maths achievers and normally-achieving children, based on both general and specific measures, especially with respect to ordering skills. In a previous study, Morsanyi et al. (2013) found that high maths achievers performed significantly better on transitive inferences, compared to both normal maths achievers and children with Developmental Dyscalculia, suggesting that high maths achievers are more effective in processing the order of transitive inference problems than both normal and low maths achievers, despite these inferences being void of any numerical content.

Regarding differences on general measures between high, normal and low maths achievers, the prevalence study into maths difficulties by Morsanyi, van Bers, McCormack and McGourty (2018) highlighted several differences between children with sustained maths difficulties, average maths achievers and high maths achievers. On average, children in the sustained maths difficulties group (compared to the other two groups) tended to; be more likely to be eligible for free school meals; be more likely to have Special Educational Needs (SEN); have newcomer status; have lower school attendance, and have lower IQ and English skills. Future research could assess group differences on domain-specific and domain-general measures, to ascertain whether there are large differences between the groups on particular measures, and whether the measures are predictive of group membership (being classified as a low, high or normal maths achiever).

5.5.6 Are ordering skills also important to numerical development amongst children educated in non-mainstream schools?

The current study only included mainstream schools in Northern Ireland. However, there are also private schools across the UK in which the teaching pedagogy differs from that of mainstream schools. Two examples of alternative educational pedagogies are the Montessori (Montessori

Academy, 2017; Montessori primary guide, 2018; Montessori Society, 2016) and Waldorf pedagogies (Edwards, 2002; Walsh & Petty, 2007), with a focus on ordering skills in children taught within the former.

The Montessori pedagogy emphasises the importance of the environment in aiding children's learning and development (Walsh & Petty, 2007). According to Montessorian theory, children are born with a mind that is predisposed towards internal order, which Montessori described as the 'mathematical brain' (Montessori Society, 2016). From children's sensorial experiences with the environment, they learn to assimilate spatial understanding and to help to construct internal order, particularly via the use of Montessori materials in the classroom, such as number rods (Montessori primary guide, 2018). By the age of four, children are ready to learn the language of mathematics, given that by now, they will have developed some of the necessary pre-requisite skills, such as being able to process internal order and to be able to both follow and complete a work cycle (Montessori primary guide, 2018). Furthermore, Montessorian theory argues that children aged between 2 and 4 years old are in a sensitive period, in which they are highly attuned to order and routine (Montessori Academy, 2017). Furthermore, children educated in a Montessorian classroom are encouraged to take learning materials from the shelves, although they are also instructed that they must assemble and disassemble the materials in the correct order when they are first taking the materials from the shelf, and when they are putting the materials back from where they came. These ideas point to the need for children in a Montessori environment having to engage their order-processing skills, even before they even begin to engage in formal maths learning. Given that I found that order-processing skills are important to maths learning for young children in mainstream schooling, of interest would be to investigate whether children who are nurtured in a Montessori learning environment would show better order-processing skills than children in mainstream education. If the Montessori-taught children do show higher performance in ordering tasks, it may be plausible to hypothesize that these children will also perform better than their peers in the mainstream school system.

5.5.7 Investigating the commonalities between order-processing skills and working memory

Finally, the results of this thesis not only show the importance of ordering skills to the development of numerical abilities, but also show how working memory abilities also support the development of these skills.

As seen throughout this thesis serial order working memory abilities correlated with maths achievement at each stage of development tested here. However, it must be noted that almost all working memory tasks involve the retention of numerical and non-numerical serial order information, either numerical or non-numerical (for example, reading span, operation span, counting span, digit span and letter span tasks). Whilst Order WM performance involved the retrieval of the serial order of a novel sequence from working memory (differing from Number ordering performance which involves the retrieval of a familiar sequence from long-term memory), there are also working memory tasks which involve the retrieval of familiar sequences from working memory (e.g. letter span and digit span), which were not tested in the current thesis. These tasks involve the retention and recall of numerical (digit span) or non-numerical sequences (letter span) in working memory, and thus provide a measure of serial order working memory skills that, unlike Order WM, involve sequences that are familiar. Given that success on these tasks at least partly relies on order-processing skills, as well as on efficient working memory skills, this suggests that working memory abilities may also underlie performance on order-processing tasks, which further underlines the importance of working memory to the development of numerical abilities.

Further research is needed to examine whether the link between order-processing skills and maths achievement is mediated by working memory abilities. In one study, Order WM did not mediate the relationship between Number ordering and arithmetic (Attout & Majerus, 2018). However, as previously mentioned, Order WM and Number differ in terms of the familiarity of the sequence to be retrieved (familiar vs. novel); which part of memory the sequence is retrieved from (long term memory vs. working memory), and the nature of the sequence (numerical vs. non-numerical). It could be the case that working memory tasks, which involve the retrieval of a familiar sequence of items from working memory, may be related to order-processing skills which also involve the retrieval of familiar sequences. Future research could involve the testing of mediation hypotheses, in order to investigate whether working memory skills for familiar content can explain the link between non-numerical ordering skills and numerical abilities in younger children, and whether they can also explain the link between numerical ordering skills and maths achievement in older children.

5.6 Conclusion

In conclusion, the results of this thesis show that order-processing skills play an important role in the development of numerical abilities across childhood. Ordering skills involving the retrieval of familiar sequences from long-term memory were found to be important skills in the early development of symbolic number knowledge in young children, whilst both numerical ordering and sequential order working memory skills play an important role in later mathematical development. Another interesting finding was that order-processing skills also were found to play a role in older children's reading development, which warrants further empirical investigation.

These results have implications for how we understand children's maths skills develop, and provide a revision to the traditional view that it is the Approximate Number System which is the precursor to symbolic number knowledge, and the subsequent development of mathematical abilities. Regarding further investigation, the OPQ and Daily events task may be suitable for early detection and as an intervention for maths difficulties, respectively. Future research may also involve assessing whether high maths achievers have exceptional order-processing skills compared to their peers; investigating whether there are numerical and non-numerical order-processing deficits in Gerstmann's syndrome, and whether children who are nurtured in alternative educational systems (e.g.

Montessori programs) show greater order-processing skills than children who are educated in the mainstream educational system.

References

Aagten-Murphy, D., Attucci, C., Daniel, N., Klaric, E., Burr, D. & Pellicano, E. (2015). Numerical estimation in children with autism. *Autism Research*, *8*, 668-681.

Abrahamse, E. L., van Dijck, J. P., & Fias, W. (2017). Grounding verbal working memory: The case of serial order. *Current Directions in Psychological Science*, *26*, 429-433.

Abrahamse, E., van Dijck, J. P., & Fias, W. (2016). How does working memory enable number-induced spatial biases? *Frontiers in Psychology*, *7*, 977.

Abrahamse, E., Van Dijck, J. P., Majerus, S., & Fias, W. (2014). Finding the answer in space: the mental whiteboard hypothesis on serial order in working memory. *Frontiers in Human Neuroscience*, *8*, 932.

Allan, N. P., Hume, L. E., Allan, D. M., Farrington, A. L. & Lonigan, C. J. (2014). Relations between inhibitory control and the development of academic skills in preschool and kindergarten: A meta-analysis. *Developmental Psychology*, *50*, 2368-2379.

Alloway, T. P., & Passolunghi, M. C. (2011). The relationship between working memory, IQ, and mathematical skills in children. *Learning and Individual Differences*, *21*, 133-137.

Ansari, D., Dhital, B., & Siong, S. C. (2006). Parametric effects of numerical distance on the intraparietal sulcus during passive viewing of rapid numerosity changes. *Brain Research*, *1067*, 181-188.

Ansari, D., Fugelsang, J. A., Dhital, B., & Venkatraman, V. (2006). Dissociating response conflict from numerical magnitude processing in the brain: an event-related fMRI study. *Neuroimage*, *32*, 799-805.

Arend, I., Ashkenazi, S., Yuen, K., Ofir, S., & Henik, A. (2017). Automatic numerical-spatial association in synaesthesia: An fMRI investigation. *Neuropsychologia*, *95*, 259-266.

Attout, L., & Majerus, S. (2018). Serial order working memory and numerical ordinal processing share common processes and predict arithmetic abilities. *British Journal of Developmental Psychology*, *36*, 285-298.

Attout, L. & Majerus, S. (2015). Working memory deficits in developmental dyscalculia: The importance of serial order. *Child Neuropsychology*, *21*, 432-450.

Attout, L., Noël, M. P. & Majerus, S. (2014). The relationship between working memory for serial order and numerical development: A longitudinal study. *Developmental Psychology*, *50*, 1667-1679.

Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences*, *4*, 417-423.

Baddeley, A. D. & Hitch, G. (1974). Working memory. *Psychology of Learning and Motivation*, *8*, 47-89.

Barth, H., Beckmann, L., & Spelke, E. S. (2008). Nonsymbolic, approximate arithmetic in children: Abstract addition prior to instruction. *Developmental Psychology*, *44*, 1466.

Barth, H., La Mont, K., Lipton, J. & Spelke, E. S. (2005). Abstract number and arithmetic in preschool children. *Proceedings of the National Academy of Sciences of the United States of America*, *102*, 14116-14121.

Barth, H. C. & Paladino, A. M. (2011). The development of numerical estimation: evidence against a representational shift. *Developmental Science. 14*, 125–135.

Bauer, P. J. (1996). What do infants recall of their lives? Memory for specific events by one-to two-year-olds. *American Psychologist*, *51*, 29.

Ben-Meir, S., Ganor-Stern, D., & Tzelgov, J. (2017). The automatic mapping of magnitude to temporal order is space-dependent. *Experimental Psychology*, *64*, 198-205.

Ben-Meir, S., Ganor-Stern, D., & Tzelgov, J. (2012). Numerical and physical magnitudes are mapped into time. *Quarterly Journal of Experimental Psychology*, *65*, 2309-2320.

Berdyyeva, T. K., & Olson, C. R. (2010). Rank signals in four areas of macaque frontal cortex during selection of actions and objects in serial order. *Journal of Neurophysiology*, *104*, 141-159.

Berteletti, I., Lucangeli, D., Piazza, M., Dehaene, S. & Zorzi, M. (2010). Numerical estimation in preschoolers. *Developmental Psychology*, *46*, 545-551.

Bonato, M., Saj, A., & Vuilleumier, P. (2016). Hemispatial neglect shows that “before” is “left”. *Neural plasticity*, 2016:2716036.

Bonato, M., Zorzi, M., & Umiltà, C. (2012). When time is space: evidence for a mental time line. *Neuroscience & Biobehavioral Reviews*, *36*, 2257-2273.

Bonny, J. W., & Lourenco, S. F. (2013). The approximate number system and its relation to early math achievement: Evidence from the preschool years. *Journal of Experimental Child Psychology*, *114*, 375-388.

Booth, J. L., & Siegler, R. S. (2008). Numerical magnitude representations influence arithmetic learning. *Child Development*, *79*, 1016-1031.

Booth, J. L., & Siegler, R. S. (2006). Developmental and individual differences in pure numerical estimation. *Developmental Psychology*, *42*, 189-201.

Brannon, E. M. (2002). The development of ordinal numerical knowledge in infancy. *Cognition*, *83*, 223-240.

Brannon, E. M., Cantlon, J. F., & Terrace, H. S. (2006). The role of reference points in ordinal numerical comparisons by rhesus macaques (Macaca mulatta). *Journal of Experimental Psychology: Animal Behavior Processes*, *32*, 120-139.

Brannon, E. M., & Terrace, H. S. (1998). Ordering of the numerosities 1 to 9 by monkeys. *Science*, *282*, 746-749.

Bugden, S., & Ansari, D. (2011). Individual differences in children's mathematical competence are related to the intentional but not automatic processing of Arabic numerals. *Cognition*, *118*, 32-44.

Bugden, S., Price, G. R., McLean, D. A., & Ansari, D. (2012). The role of the left intraparietal sulcus in the relationship between symbolic number processing and children's arithmetic competence. *Developmental Cognitive Neuroscience*, *2*, 448-457.

Bull, R., Espy, K. A., & Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years. *Developmental Neuropsychology*, *33*, 205-228.

Bull, R., & Lee, K. (2014). Executive functioning and mathematics achievement. *Child Development Perspectives*, *8*, 36-41.

Bull, R. & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: Inhibition, switching, and working memory. *Developmental Neuropsychology*, *19*, 273-293.

Butterworth B. (2005) Developmental Dyscalculia. In: Campbell, J. D. (Eds). *The Handbook of Mathematical Cognition.* New York: Psychology Press. 455–469.

Cantlon, J. F. & Brannon, E. M. (2007). Basic math in monkeys and college students. *PLoS Biology*, *5*, e328.

Cantlon, J. F., & Brannon, E. M. (2006). Shared system for ordering small and large numbers in monkeys and humans. *Psychological Science*, *17*, 401-406.

Cargnelutti, E., Tomasetto, C., & Passolunghi, M. C. (2017). How is anxiety related to math performance in young students? A longitudinal study of Grade 2 to Grade 3 children. *Cognition and Emotion*, *31*, 755-764.

Carota, A., Di Pietro, M., Ptak, R., Poglia, D., & Schnider, A. (2004). Defective spatial imagery with pure Gerstmann's syndrome. *European Neurology*, *52*, 1-6.

Casarotti, M., Michielin, M., Zorzi, M., & Umiltà, C. (2007). Temporal order judgment reveals how number magnitude affects visuospatial attention. *Cognition*, *102*, 101-117.

Cassia, V. M., Picozzi, M., Girelli, L., & de Hevia, M. D. (2012). Increasing magnitude counts more: asymmetrical processing of ordinality in 4-month-old infants. *Cognition*, *124*, 183-193.

Castronovo, J., & Göbel, S. M. (2012). Impact of high mathematics education on the number sense. *PloS one*, *7*, e33832.

Chen, Q. & Li, J. (2014). Association between individual differences in non-symbolic number acuity and math performance: A meta-analysis. *Acta Psychologica*, *148*, 163-172.

Cheung, C. N., & Lourenco, S. F. (2016). The associations between space and order in numerical and non-numerical sequences. *Consciousness and Cognition*, *45*, 124-134.

Clayton, S. & Gilmore, C. (2015). Inhibition in dot comparison tasks. ZDM: *Mathematics Education*, 47, 759-770.

Clayton, S., Gilmore, C., & Inglis, M. (2015). Dot comparison stimuli are not all alike: The effect of different visual controls on ANS measurement. *Acta Psychologica*, *161*, 177-184.

Clements, D. H., Sarama, J. & Germeroth, C. (2016). Learning executive function and early mathematics: Directions of causal relations. *Early Childhood Research Quarterly*, *36*, 79-90.

Cohen, D. J. & Blanc-Goldhammer, D. (2011). Numerical bias in bounded and unbounded number line tasks. *Psychonomic Bulletin & Review*, *18*, 331-338.

Colomé, À. & Noël, M. P. (2012). One first? Acquisition of the cardinal and ordinal uses of numbers in preschoolers. *Journal of Experimental Child Psychology*, *113*, 233-247.

Council for the Curriculum, Examinations and Assessment (2016). Mathematics and Numeracy. Retrieved 6th June 2017 from http://ccea.org.uk/curriculum/key_stage_1_2/areas_learning/mathematics_and_numeracy

Council for the Curriculum, Examinations and Assessment (2014a). Statutory Requirements Key Stage 1 - Mathematics and Numeracy. Retrieved 6th June 2017 from http://ccea.org.uk/sites/default/files/docs/curriculum/area_of_learning/mathematics_and_numeracy/ks1_statutory_requirements.pdf

Council for the Curriculum, Examinations and Assessment (2014b). Statutory Requirements Key Stage 2 - Mathematics and Numeracy. Retrieved 6th June 2017 from http://ccea.org.uk/sites/default/files/docs/curriculum/area_of_learning/mathematics_and_numeracy/ks2_statutory_requirements.pdf

Council for the Curriculum, Examinations and Assessment (2007). The Northern Ireland Curriculum: Primary. Retrieved 6th September 2018 from http://ccea.org.uk/sites/default/files/docs/curriculum/area_of_learning/fs_northern_ireland_curriculum_primary.pdf

Cowan, N., Hogan, T. P., Alt, M., Green, S., Cabbage, K. L., Brinkley, S., & Gray, S. (2017). Short-term Memory in Childhood Dyslexia: Deficient Serial Order in Multiple Modalities. *Dyslexia*, *23*, 209-233.

Cragg, L., & Gilmore, C. (2014). Skills underlying mathematics: The role of executive function in the development of mathematics proficiency. *Trends in Neuroscience and Education*, *3*, 63-68.

Crollen, V., & Noël, M. P. (2015). Spatial and numerical processing in children with high and low visuospatial abilities. *Journal of Experimental Child Psychology*, *132*, 84-98.

Crollen, V., Vanderclausen, C., Allaire, F., Pollaris, A., & Noël, M. P. (2015). Spatial and numerical processing in children with non-verbal learning disabilities. *Research in Developmental Disabilities*, *47*, 61-72.

Davidson, K., Eng, K., & Barner, D. (2012). Does learning to count involve a semantic induction? *Cognition*, *123*, 162-173.

Davis-Kean, P. E. (2005). The influence of parent education and family income on child achievement: The indirect role of parental expectations and the home environment. *Journal of Family Psychology*, *19,* 294–304.

Deary, I. J., Strand, S., Smith, P., & Fernandes, C. (2007). Intelligence and educational achievement. *Intelligence*, *35*, 13-21.

Dehaene, S. (1997). *The Number Sense*. New York: Oxford University Press.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, *122*, 371-396.

Dehaene, S., Dupoux, E. & Mehler, J. (1990). Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 626–641.

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology*, *20*, 487-506.

De Hevia, M. D., Addabbo, M., Nava, E., Croci, E., Girelli, L., & Cassia, V. M. (2017). Infants' detection of increasing numerical order comes before detection of decreasing number. *Cognition*, *158*, 177-188.

Department for Employment and Learning in Northern Ireland (2013). The International Survey of Adult Skills 2012: Adult literacy, numeracy and problem solving skills in Northern Ireland. Retrieved 6th June 2017 from https://www.economyni.gov.uk/publications/international-survey-adult-skills

Department of Education (2017). Statistical bulletin 5/2017 - Year 12 and 14 examination performance at post-primary schools in Northern Ireland 2015/16. Retrieved 6th June from https://www.education-ni.gov.uk/sites/default/files/publications/education/Statistical-Bulletin-5-2017-Year-12-and-Year-14-examination-performance-at-Post-Primary-Schools-in-Northern-Ireland%202015-16.PDF

Department of Education (2011). Count, read, succeed - a strategy to improve outcomes in literacy and numeracy. Retrieved 2nd July 2017 from https://www.education-ni.gov.uk/sites/default/files/publications/de/count-read-succeed-power-point-presentation.pdf

De Smedt, B., Janssen, R., Bouwens, K., Verschaffel, L., Boets, B., & Ghesquière, P. (2009). Working memory and individual differences in mathematics achievement: A longitudinal study from first grade to second grade. *Journal of Experimental Child Psychology*, *103*, 186-201.

De Smedt, B., Noël, M. P., Gilmore, C. & Ansari, D. (2013). How do symbolic and non-symbolic numerical magnitude processing skills relate to individual differences in children's mathematical skills? A review of evidence from brain and behavior. *Trends in Neuroscience and Education*, *2*, 48-55.

De Smedt, B., Taylor, J., Archibald, L., & Ansari, D. (2010). How is phonological processing related to individual differences in children's arithmetic skills? *Developmental Science*, *13*, 508-520.

De Smedt, B., Verschaffel, L., & Ghesquière, P. (2009). The predictive value of numerical magnitude comparison for individual differences in mathematics achievement. *Journal of Experimental Child Psychology*, *103*, 469-479.

DeStefano, D. & LeFevre, J. A. (2004). The role of working memory in mental arithmetic. *European Journal of Cognitive Psychology*, *16*, 353-386.

Durand, M., Hulme, C., Larkin, R., & Snowling, M. (2005). The cognitive foundations of reading and arithmetic skills in 7-to 10-year-olds. *Journal of Experimental Child Psychology*, *91*, 113-136.

Ecker, U. K., Lewandowsky, S., Oberauer, K., & Chee, A. E. (2010). The components of working memory updating: an experimental decomposition and individual differences. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*, 170-189.

Edwards, C. P. (2002). Three Approaches from Europe: Waldorf, Montessori, and Reggio Emilia. *Early Childhood Research & Practice, 4*, 1-14.

Eurydice at NFER – National Foundation for Educational Research: Compulsory age of starting school in European countries (2012). Retrieved 10th August 2016 from https://www.nfer.ac.uk/nfer/eurydice/publications/compulsory-age-of-starting-school.cfm

Fazio, L. K., Bailey, D. H., Thompson, C. A., & Siegler, R. S. (2014). Relations of different types of numerical magnitude representations to each other and to mathematics achievement. *Journal of Experimental Child Psychology*, *123*, 53-72.

Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Sciences*, *8*, 307-314.

Fias, W., & van Dijck, J. P. (2016). The temporary nature of number—space interactions. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale*, *70*, 33-40.

Fias, W., Lammertyn, J., Caessens, B., & Orban, G. A. (2007). Processing of abstract ordinal knowledge in the horizontal segment of the intraparietal sulcus. *Journal of Neuroscience*, *27*, 8952-8956.

Fivush, R., & Hammond, N. (1990). Autobiographical memory across the preschool years: toward reconceptualising childhood amnesia. In R. Fivush and J. Hudson (Eds.), *Knowing and Remembering in Young Children.* New York: Cambridge University Press.

Franklin, M. S., & Jonides, J. (2009). Order and magnitude share a common representation in parietal cortex. *Journal of Cognitive Neuroscience*, *21*, 2114-2120.

Friedman, W. J. (2005). Developmental and cognitive perspectives on humans' sense of the times of past and future events. *Learning and Motivation*, *36*, 145-158.

Friedman, W. J. (2002). Children's knowledge of the future distances of daily activities and annual events. *Journal of Cognition and Development*, *3*, 333-356.

Friedman, W. J. (2000a). The development of children's knowledge of the times of future events. *Child Development*, *71*, 913-932.

Friedman, W. J. (2000b). Time in psychology. In P. J. N. Baert (Ed.), Time in contemporary intellectual thought. Amsterdam: Elsevier.

Friedman, W. J. (1990). Children's representations of the pattern of daily activities. *Child Development*, *61*, 1399-1412.

Friedman, W. J. (1989). The representation of temporal structure in children, adolescents and adults. *Advances in Psychology*, 59, 259-304.

Friedman, W. J. (1986). The development of children's knowledge of temporal structure. *Child Development*, 1386-1400.

Friedman, W. J. (1983). Image and verbal processes in reasoning about the months of the year. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *10*, 126-132.

Friedman, W. J. (1977). The development of children's knowledge of cyclic aspects of time. *Child Development*. 48, 1593-1599.

Friedman, W. J., & Brudos, S. L. (1988). On routes and routines: The early development of spatial and temporal representations. *Cognitive Development*, 3, 167-182.

Friso-van den Bos, I., van der Ven, S. H., Kroesbergen, E. H., & van Luit, J. E. (2013). Working memory and mathematics in primary school children: A meta-analysis. *Educational Research Review*, *10*, 29-44.

Fry, A. F., & Hale, S. (1996). Processing speed, working memory, and fluid intelligence: Evidence for a developmental cascade. *Psychological Science*, *7*, 237-241.

Fulbright, R. K., Manson, S. C., Skudlarski, P., Lacadie, C. M., & Gore, J. C. (2003). Quantity determination and the distance effect with letters, numbers, and shapes: a functional MR imaging study of number processing. *American Journal of Neuroradiology*, *24*, 193-200.

Gelman, R. & Gallistel, C. R. (1978). *The child's understanding of number*. Washington, DC: American Psychological Association.

Geary, D. C. (1993). Mathematical disabilities: Cognitive, neuropsychological, and genetic components. *Psychological Bulletin*, *114*, 345-362.

Geary, D. C. (2013). Early foundations for mathematics learning and their relations to learning disabilities. *Current Directions in Psychological Science*, *22*, 23-27.

Gibbon, J. & Church, R. M. (1981). Time left: linear versus logarithmic subjective time. *Journal of Experimental Psychology: Animal Behaviour Processes*, *7*, 87.

Gilmore, C., Attridge, N., Clayton, S., Cragg, L., Johnson, S., Marlow, N. … & Inglis, M. (2013). Individual differences in inhibitory control, not non-verbal number acuity, correlate with mathematics achievement. *PLoS One*, *8*, e67374.

Gilmore, C., Cragg, L., Hogan, G., & Inglis, M. (2016). Congruency effects in dot comparison tasks: Convex hull is more important than dot area. *Journal of Cognitive Psychology*, *28*, 923-931.

Gilmore, C., Attridge, N., De Smedt, B., & Inglis, M. (2014). Measuring the approximate number system in children: exploring the relationships among different tasks. *Learning and Individual Differences*, *29*, 50-58.

Gilmore, C. K., McCarthy, S. E., & Spelke, E. S. (2010). Non-symbolic arithmetic abilities and mathematics achievement in the first year of formal schooling. *Cognition*, *115*, 394-406.

Ginsburg, V., Archambeau, K., van Dijck, J. P., Chetail, F., & Gevers, W. (2017). Coding of serial order in verbal, visual and spatial working memory. *Journal of Experimental Psychology: General*, *146*, 632-650.

Ginsburg, H. P., & Baroody, A. J. (2003). *Test of Early Mathematics Ability, Third Edition.* Austin, TX: Pro- Ed

Ginsburg, V., & Gevers, W. (2015). Spatial coding of ordinal information in short-and long-term memory. *Frontiers in Human Neuroscience*, *9*, 8.

Goffin, C., & Ansari, D. (2016). Beyond magnitude: Judging ordinality of symbolic number is unrelated to magnitude comparison and independently relates to individual differences in arithmetic. *Cognition*, *150*, 68-76.

Halberda, J., Ly, R., Wilmer, J. B., Naiman, D. Q., & Germine, L. (2012). Number sense across the lifespan as revealed by a massive Internet-based sample. *Proceedings of the National Academy of Sciences*, *109*, 11116-11120.

Halberda, J., Mazzocco, M. M. & Feigenson, L. (2008). Individual differences in nonverbal number acuity predict maths achievement. *Nature, 455*, 665-668.

Hannula, M. M., & Lehtinen, E. (2005). Spontaneous focusing on numerosity and mathematical skills of young children. *Learning and Instruction*, *15*, 237-256.

Hill, F., Mammarella, I. C., Devine, A., Caviola, S., Passolunghi, M. C., & Szűcs, D. (2016). Maths anxiety in primary and secondary school students: Gender differences, developmental changes and anxiety specificity. *Learning and Individual Differences*, *48*, 45-53

Hobbs, G., & Vignoles, A. (2010). Is children's free school meal 'eligibility' a good proxy for family income? *British Educational Research Journal*, *36*, 673-690.

Holloway, I. D. & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: the distance effect and children's mathematical competence. *Journal of Experimental Child Psychology, 103*, 17-29.

Holloway, I. D., Price, G. R., & Ansari, D. (2010). Common and segregated neural pathways for the processing of symbolic and nonsymbolic numerical magnitude: An fMRI study. *Neuroimage*, *49*, 1006-1017.

Holmes, J., & Adams, J. W. (2006). Working memory and children's mathematical skills: Implications for mathematical development and mathematics curricula. *Educational Psychology*, *26*, 339-366.

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews Neuroscience*, *6*, 435-448.

Hyde, D. C., Khanum, S., & Spelke, E. S. (2014). Brief non-symbolic, approximate number practice enhances subsequent exact symbolic arithmetic in children. *Cognition*, *131*, 92-107.

Iuculano, T., Tang, J., Hall, C.W. & Butterworth, B. (2008). Core information processing deficits in developmental dyscalculia and low numeracy. *Developmental Science, 11*, 669–680.

Inglis, M., Attridge, N., Batchelor, S., & Gilmore, C. (2011). Non-verbal number acuity correlates with symbolic mathematics achievement: But only in children. *Psychonomic Bulletin & Review*, *18*, 1222-1229.

Inglis, M. & Gilmore, C. (2014). Indexing the approximate number system. *Acta Psychologica*, *145*, 147-155.

Inglis, M., & Gilmore, C. (2013). Sampling from the mental number line: How are approximate number system representations formed? *Cognition*, *129*, 63-69.

InterNations (2018). The Chinese education system. Retrieved 7th September 2018 from: https://www.internations.org/china-expats/guide/29461-family-children-education/the-chinese-education-system-17856

Ischebeck, A., Heim, S., Siedentopf, C., Zamarian, L., Schocke, M., Kremser, C. …& Delazer, M. (2008). Are numbers special? Comparing the generation of verbal materials from ordered categories (months) to numbers and other categories (animals) in an fMRI study. *Human Brain Mapping*, *29*, 894-909.

Jacob, R., & Parkinson, J. (2015). The potential for school-based interventions that target executive function to improve academic achievement: A review. *Review of Educational Research*, *85*, 512-552.

Jansen, B. R., Louwerse, J., Straatemeier, M., Van der Ven, S. H., Klinkenberg, S., & Van der Maas, H. L. (2013). The influence of experiencing success in math on math anxiety, perceived math competence, and math performance. *Learning and Individual Differences*, *24*, 190-197.

Jordan, J. A., Wylie, J., & Mulhern, G. (2015). Mathematics and reading difficulty subtypes: minor phonological influences on mathematics for 5–7-years-old. *Frontiers in Psychology*, *6*, 221.

Jordan, J. A., Wylie, J., & Mulhern, G. (2010). Phonological awareness and mathematical difficulty: A longitudinal perspective. *British Journal of Developmental Psychology*, *28*, 89-107.

Just Landed (2018a). Public Schools: The Canadian public school system. Retrieved 7th September 2018 from https://www.justlanded.com/english/Canada/Canada-Guide/Education/Public-Schools

Just Landed (2018b). The American school system: Grades, school hours and terms. Retrieved 7th September 2018 from https://www.justlanded.com/english/United-States/USA-Guide/Education/The-American-school-system

Kaufman, E. L., Lord, M. W., Reese, T. W. & Volkmann, J. (1949). The discrimination of visual number. *The American Journal of Psychology*, 498-525.

Kaufmann, L., Vogel, S. E., Starke, M., Kremser, C., & Schocke, M. (2009). Numerical and non-numerical ordinality processing in children with and without developmental dyscalculia: Evidence from fMRI. *Cognitive Development*, *24*, 486-494.

Kaufmann, L., & von Aster, M. (2012). The diagnosis and management of dyscalculia. *Deutsches Ärzteblatt International*, *109*, 767-778.

Kesner, R. P., & Holbrook, T. (1987). Dissociation of item and order spatial memory in rats following medial prefrontal cortex lesions. *Neuropsychologia*, *25*, 653-664.

Klein, J. S. & Bisanz, J. (2000). Preschoolers doing arithmetic: The concepts are willing but the working memory is weak. *Canadian Journal of Experimental Psychology*, *54*, 105−115.

Knops, A., & Willmes, K. (2014). Numerical ordering and symbolic arithmetic share frontal and parietal circuits in the right hemisphere. *Neuroimage*, *84*, 786-795.

Kolkman, M. E., Kroesbergen, E. H., & Leseman, P. P. (2013). Early numerical development and the role of non-symbolic and symbolic skills. *Learning and instruction*, *25*, 95-103.

Lan, X., Legare, C. H., Ponitz, C. C., Li, S., & Morrison, F. J. (2011). Investigating the links between the subcomponents of executive function and academic achievement: A cross-cultural analysis of Chinese and American preschoolers. *Journal of Experimental Child Psychology*, *108*, 677-692.

Laski, E. V., & Siegler, R. S. (2007). Is 27 a big number? Correlational and causal connections among numerical categorization, number line estimation, and numerical magnitude comparison. *Child Development*, *78*, 1723-1743.

Leclercq, A. L., & Majerus, S. (2010). Serial-order short-term memory predicts vocabulary development: Evidence from a longitudinal study. *Developmental Psychology, 46,* 417–427.

Le Corre, M., & Carey, S. (2007). One, two, three, four, nothing more: An investigation of the conceptual sources of the verbal counting principles. *Cognition*, *105*, 395-438.

Leibovich, T., & Ansari, D. (2016). The symbol-grounding problem in numerical cognition: A review of theory, evidence, and outstanding questions. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale*, *70*, 1-12.

Li, Y., Zhang, M., Chen, Y., Zhu, X., Deng, Z., & Yan, S. (2017). Children’s Non-symbolic, Symbolic Addition and Their Mapping Capacity at 4–7 Years Old. *Frontiers in Psychology*, *8*, 1203.

Libertus, M. E., Feigenson, L., & Halberda, J. (2011). Preschool acuity of the approximate number system correlates with school math ability. *Developmental Science*, *14*, 1292-1300.

Libertus, M. E., Odic, D., & Halberda, J. (2012). Intuitive sense of number correlates with math scores on college-entrance examination. *Acta Psychologica*, *141*, 373-379.

Link, T., Huber, S., Nuerk, H. C., & Moeller, K. (2014). Unbounding the mental number line—new evidence on children's spatial representation of numbers. *Frontiers in Psychology*, *4*, 1021.

Lipton, J. S., & Spelke, E. S. (2005). Preschool children's mapping of number words to nonsymbolic numerosities. *Child Development*, *76*, 978-988.

Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review*, *91*, 295.

Lonnemann, J., Linkersdörfer, J., Hasselhorn, M., & Lindberg, S. (2011). Symbolic and non-symbolic distance effects in children and their connection with arithmetic skills. *Journal of Neurolinguistics*, *24*, 583-591.

Lonnemann, J., Linkersdörfer, J., Nagler, T., Hasselhorn, M., & Lindberg, S. (2013). Spatial representations of numbers and letters in children. *Frontiers in Psychology*, *4*, 544.

Lourenco, S. F., Bonny, J. W., Fernandez, E. P., & Rao, S. (2012). Nonsymbolic number and cumulative area representations contribute shared and unique variance to symbolic math competence. *Proceedings of the National Academy of Sciences*, *109*, 18737-18742.

Lyons, I. M., & Ansari, D. (2015). Numerical order processing in children: From reversing the distance-effect to predicting arithmetic. *Mind, Brain, and Education*, *9*, 207-221.

Lyons, I. M., & Ansari, D. (2009). The cerebral basis of mapping nonsymbolic numerical quantities onto abstract symbols: An fMRI training study. *Journal of Cognitive Neuroscience*, *21*, 1720-1735.

Lyons, I. M., Ansari, D., & Beilock, S. L. (2015). Qualitatively different coding of symbolic and nonsymbolic numbers in the human brain. *Human Brain Mapping*, *36*, 475-488.

Lyons, I. M. & Beilock, S. L. (2011). Numerical ordering ability mediates the relation between number-sense and arithmetic competence. *Cognition, 121*, 256–261.

Lyons, I. M., Price, G. R., Vaessen, A., Blomert, L. & Ansari, D. (2014). Numerical predictors of arithmetic success in grades 1–6. *Developmental Science*, *17*, 714-726.

Lyons, I. M., Vogel, S. E., & Ansari, D. (2016). On the ordinality of numbers: A review of neural and behavioral studies. *Progress in Brain Research*, 227, 187-221.

Magnani, B., & Musetti, A. (2017). Innate and cultural spatial time: A developmental perspective. *Frontiers in Human Neuroscience*, *11*, 215.

Majerus, S., & Boukebza, C. (2013). Short-term memory for serial order supports vocabulary development: New evidence from a novel word learning paradigm. *Journal of Experimental Child Psychology, 116,* 811–828.

Majerus, S., Heiligenstein, L., Gautherot, N., Poncelet, M., & Linden, M. (2009). Impact of auditory selective attention on verbal short-term memory and vocabulary development. *Journal of Experimental Child Psychology, 103,* 66–86.

Majerus, S., Poncelet, M., Greffe, C., & Van der Linden, M. (2006). Relations between vocabulary development and verbal short-term memory: The relative importance of short-term memory for serial order and item information. *Journal of Experimental Child Psychology*, *93*, 95-119.

Maloney, E. A., Risko, E. F., Preston, F., Ansari, D., & Fugelsang, J. (2010). Challenging the reliability and validity of cognitive measures: The case of the numerical distance effect. *Acta Psychologica*, *134*, 154-161.

Mammarella, I. C., Hill, F., Devine, A., Caviola, S., & Szűcs, D. (2015). Math anxiety and developmental dyscalculia: a study on working memory processes. *Journal of Clinical and Experimental Neuropsychology*, *37*, 878-887.

Mammarella, I. C., Lucangeli, D., & Cornoldi, C. (2010). Spatial working memory and arithmetic deficits in children with nonverbal learning difficulties. *Journal of Learning Disabilities*, *43*, 455-468.

Mandler, G. & Shebo, B. J. (1982). Subitizing: an analysis of its component processes. *Journal of Experimental Psychology: General*, 111, 11-22.

Matejko, A. A., & Ansari, D. (2016). Trajectories of symbolic and nonsymbolic magnitude processing in the first year of formal schooling. *PloS one*, *11*, e0149863.

Matejko, A. A., Price, G. R., Mazzocco, M. M., & Ansari, D. (2013). Individual differences in left parietal white matter predict math scores on the Preliminary Scholastic Aptitude Test. *Neuroimage*, *66*, 604-610.

Mazzocco, M. M., Feigenson, L., & Halberda, J. (2011). Impaired acuity of the approximate number system underlies mathematical learning disability (dyscalculia). *Child Development*, *82*, 1224-1237.

McCaskey, U., Von Aster, M., O'Gorman Tuura, R., & Kucian, K. (2017). Adolescents with Developmental Dyscalculia Do Not Have a Generalized Magnitude Deficit–Processing of Discrete and Continuous Magnitudes. *Frontiers in Human Neuroscience*, *11*, 102.

McCrink, K., & Wynn, K. (2004). Large-number addition and subtraction by 9-month-old infants. *Psychological Science*, *15*, 776-781.

McKenzie, B., Bull, R., & Gray, C. (2003). The effects of phonological and visual-spatial interference on children's arithmetical performance. *Educational and Child Psychology*, *20*, 93-108.

Mejias, S., Grégoire, J., & Noël, M. P. (2012). Numerical estimation in adults with and without developmental dyscalculia. *Learning and Individual Differences*, 22, 164-170.

Melby-Lervåg, M., Lyster, S. A. H., & Hulme, C. (2012). Phonological skills and their role in learning to read: a meta-analytic review. *Psychological Bulletin*, *138*, 322-352.

Meyer, M. L., Salimpoor, V. N., Wu, S. S., Geary, D. C., & Menon, V. (2010). Differential contribution of specific working memory components to mathematics achievement in 2nd and 3rd graders. *Learning and Individual Differences*, *20*, 101-109.

Michie, S. (1985). Development of absolute and relative concepts of number in preschool children. *Developmental Psychology*, *21*, 247-252.

Miller, S. P., & Hudson, P. J. (2007). Using evidence-based practices to build mathematics competence related to conceptual, procedural, and declarative knowledge. *Learning Disabilities Research & Practice*, *22*, 47-57.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A. & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology*, *41*, 49-100.

Montessori Academy (2017). How do you encourage your children to pack away independently? Retrieved 10th September 2018 from https://montessoriacademy.com.au/children-pack-away-indepedently/

Montessori primary guide (2018). Introduction to mathematics. Retrieved 10th September 2018 from http://www.infomontessori.com/mathematics/introduction.htm

Montessori Society (2016). Approach to maths. Retrieved 10th September 2018 from https://www.montessorisociety.org.uk/Articles/4403559

Morsanyi, K., Devine, A., Nobes, A. & Szűcs, D. (2013). The link between logic, mathematics and imagination. Evidence from children with developmental dyscalculia and mathematically gifted children. *Developmental Science, 16,* 542-553.

Morsanyi, K., McCormack, T., & O'Mahony, E. (2018). The link between deductive reasoning and mathematics. *Thinking & Reasoning*, *24*, 234-257.

Morsanyi, K., O'Mahony, E., & McCormack, T. (2017). Number comparison and number ordering as predictors of arithmetic performance in adults: Exploring the link between the two skills, and investigating the question of domain-specificity. *The Quarterly Journal of Experimental Psychology*, *70*, 2497-2517.

Morsanyi, K., van Bers, B. M., McCormack, T., & McGourty, J. (2018). The prevalence of specific learning disorder in mathematics and comorbidity with other developmental disorders in primary school-age children. *British Journal of Psychology*, *109*, 917-940.

Morsanyi, K., van Bers, B. M., O'Connor, P. A., & McCormack, T. (2018). Developmental Dyscalculia is characterized by Order Processing Deficits: Evidence from Numerical and Non-Numerical Ordering Tasks. *Developmental Neuropsychology*, *43*, 595-621.

Moyer, R. S. & Landauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature*, 215, 1519–1520.

Mundy, E., & Gilmore, C. K. (2009). Children's mapping between symbolic and nonsymbolic representations of number. *Journal of Experimental Child Psychology*, *103*, 490-502.

National Center for Learning Disabilities: Understanding Dyscalculia (2007). Retrieved 17th October 2017 from http://www.ldonline.org/article/13709/

National Foundation for Educational Research (2013). Compulsory age of starting school in European countries. Retrieved 16th June 2015 from https://www.nfer.ac.uk/eurydice/compulsory-age-of-starting-school.html

Nelson, K. (1998). *Language in cognitive development: The emergence of the mediated mind*. Cambridge University Press.

Nelson, K. (1986). Event knowledge: Structure and function in development. Hillsdale, NJ: Erlbaum.

Nieder, A. (2009). Prefrontal cortex and the evolution of symbolic reference. *Current Opinion in Neurobiology*, 19, 99–108.

Nieder, A., & Dehaene, S. (2009). Representation of number in the brain. *Annual Review of Neuroscience*, *32*, 185-208.

Ninokura, Y., Mushiake, H., & Tanji, J. (2003). Representation of the temporal order of visual objects in the primate lateral prefrontal cortex. *Journal of Neurophysiology*, *89*, 2868-2873.

Noël, M. P. (2009). Counting on working memory when learning to count and to add: a preschool study. *Developmental Psychology*, *45*, 1630-1643.

Northern Ireland Audit Office (2009). Improving Adult Literacy and Numeracy. Retrieved 24th June 2016 from https://www.niauditoffice.gov.uk/publication/improving-adult-literacy-and-numeracy

Northern Ireland Audit Office (2006). Improving Literacy and Numeracy in Schools. Retrieved 24th June 2016 from https://www.niauditoffice.gov.uk/publication/improving-literacy-and-numeracy-schools

Northern Ireland Statistics and Research Agency (2010). Northern Ireland Multiple Deprivation Measure 2010: Blueprint Document. February 2010. Retrieved 23rd June, 2014, from http://www.nisra.gov.uk/deprivation/archive/Updateof2005Measures/NIMDM_2010_Blueprint_Document.pdf

Nosworthy, N., Bugden, S., Archibald, L., Evans, B., & Ansari, D. (2013). A two-minute paper-and-pencil test of symbolic and nonsymbolic numerical magnitude processing explains variability in primary school children's arithmetic competence. *PloS one*, *8*, e67918.

O'Connor, P. A., Morsanyi, K., & McCormack, T. (2018). Young children's non-numerical ordering ability at the start of formal education longitudinally predicts their symbolic number skills and academic achievement in maths. *Developmental science*, e12645.

O'Connor, P. A., Morsanyi, K., & McCormack, T. (In preparation). Which skills at the beginning of primary school predict maths 3 years later? *Manuscript in preparation.*

Odic, D., Le Corre, M., & Halberda, J. (2015). Children’s mappings between number words and the approximate number system. *Cognition*, *138*, 102-121.

Oliveri, M., Vicario, C. M., Salerno, S., Koch, G., Turriziani, P., Mangano, R. ... & Caltagirone, C. (2008). Perceiving numbers alters time perception. *Neuroscience letters*, *438*, 308-311.

Organisation for Economic Co-operation and Development (2013). Survey of adult skills first results: England and Northern Ireland. Retrieved 1st July 2017 from http://www.oecd.org/skills/piaac/Country%20note%20-%20United%20Kingdom.pdf

Park, J., & Brannon, E. M. (2014). Improving arithmetic performance with number sense training: An investigation of underlying mechanism. *Cognition*, *133*, 188-200.

Park, J., & Brannon, E. M. (2013). Training the approximate number system improves math proficiency. *Psychological Science*, *24*, 2013-2019.

Passolunghi, M. C., Cargnelutti, E. & Pastore, M. (2014). The contribution of general cognitive abilities and approximate number system to early mathematics. *British Journal of Educational Psychology*, *84*, 631-649.

Passolunghi, M. C., & Cornoldi, C. (2008). Working memory failures in children with arithmetical difficulties. *Child Neuropsychology*, *14*, 387-400.

Passolunghi, M. C., & Lanfranchi, S. (2012). Domain-specific and domain-general precursors of mathematical achievement: A longitudinal study from kindergarten to first grade. *British Journal of Educational Psychology*, *82*, 42-63.

Passolunghi, M. C. & Mammarella, I. C. (2012). Selective spatial working memory impairment in a group of children with mathematics learning disabilities and poor problem-solving skills. *Journal of Learning Disabilities*, *45*, 341-350.

Passolunghi, M. C., & Mammarella, I. C. (2010). Spatial and visual working memory ability in children with difficulties in arithmetic word problem solving. *European Journal of Cognitive Psychology*, *22*, 944-963.

Passolunghi, M. C., Mammarella, I. C., & Altoè, G. (2008). Cognitive abilities as precursors of the early acquisition of mathematical skills during first through second grades. *Developmental Neuropsychology*, *33*, 229-250.

Passolunghi, M. C., & Pazzaglia, F. (2004). Individual differences in memory updating in relation to arithmetic problem solving. *Learning and Individual Differences*, *14*, 219-230.

Passolunghi, M. C., & Siegel, L. S. (2001). Short-term memory, working memory, and inhibitory control in children with difficulties in arithmetic problem solving. *Journal of Experimental Child Psychology*, *80*, 44-57.

Passolunghi, M. C., Vercelloni, B. & Schadee, H. (2007). The precursors of mathematics learning: Working memory, phonological ability and numerical competence. *Cognitive Development*, *22*, 165-184.

Peng, P., Namkung, J., Barnes, M., & Sun, C. (2016). A meta-analysis of mathematics and working memory: Moderating effects of working memory domain, type of mathematics skill, and sample characteristics. *Journal of Educational Psychology*, *108*, 455.

Peng, A. S., Yen, J., & Chen, C. H. (2012). Application of the Order of Operations (BODMAS) into Design Thinking. *Bulletin of Japanese Society for the Science of Design*, *59*, 321-330.

Penner-Wilger, M., Fast, L., LeFevre, J., Smith-Chant, B. L., Skwarchuk, S., Kamawar, D., et al (2007). The foundations of numeracy: Subitizing, finger agnosia, and fine-motor ability. In D. S. McNamara & J. G. Trafton (Eds.), *Proceedings of the 29th Annual Cognitive Science Society* (pp. 1385–1390). Austin, TX: Cognitive Science Society.

Perez, T. M., Majerus, S., & Poncelet, M. (2013). Impaired short-term memory for order in adults with dyslexia. *Research in Developmental Disabilities*, *34*, 2211-2223.

Perez, T. M., Majerus, S., & Poncelet, M. (2012). The contribution of short-term memory for serial order to early reading acquisition: Evidence from a longitudinal study. *Journal of Experimental Child Psychology*, *111*, 708-723.

Petrazzini, M. E. M., Lucon-Xiccato, T., Agrillo, C., & Bisazza, A. (2015). Use of ordinal information by fish. *Scientific Reports*, *5*, 15497.

Piazza, M., Facoetti, A., Trussardi, A. N., Berteletti, I., Conte, S., Lucangeli, D.…& Zorzi, M. (2010). Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. *Cognition, 116*, 33-41.

Piazza, M., Izard, V., Pinel, P., Le Bihan, D., & Dehaene, S. (2004). Tuning curves for approximate numerosity in the human intraparietal sulcus. *Neuron*, *44*, 547-555.

Pica, P., Lemer, C., Izard, V. & Dehaene, S. (2004). Exact and approximate arithmetic in an Amazonian indigene group. *Science*, *306*, 499–503.

Picozzi, M., de Hevia, M. D., Girelli, L., & Cassia, V. M. (2010). Seven-month-olds detect ordinal numerical relationships within temporal sequences. *Journal of Experimental Child Psychology*, *107*, 359-367.

Price, G. R., Palmer, D., Battista, C., & Ansari, D. (2012). Nonsymbolic numerical magnitude comparison: Reliability and validity of different task variants and outcome measures, and their relationship to arithmetic achievement in adults. *Acta Psychologica*, *140*, 50-57.

Price, G. R., Holloway, I., Räsänen, P., Vesterinen, M., & Ansari, D. (2007). Impaired parietal magnitude processing in developmental dyscalculia. *Current Biology*, *17*, R1042-R1043.

Pro Bono Economics (2014) Cost of outcomes associated with low levels of adult numeracy in the UK. Retrieved 7th June 2017 from https://www.nationalnumeracy.org.uk/cost-outcomes-associated-low-levels-adult-numeracy-uk-2014

Raghubar, K. P., Barnes, M. A. & Hecht, S. A. (2010). Working memory and mathematics: A review of developmental, individual difference, and cognitive approaches. *Learning and Individual Differences*, *20*, 110-122.

Rasmussen, C. & Bisanz, J. (2005). Representation and working memory in early arithmetic. *Journal of Experimental Child Psychology*, 91, 137−157.

Reynvoet, B., & Sasanguie, D. (2016). The symbol grounding problem revisited: A thorough evaluation of the ANS mapping account and the proposal of an alternative account based on symbol–symbol associations. *Frontiers in Psychology*, *7*, 1581.

Roth, B., Becker, N., Romeyke, S., Schäfer, S., Domnick, F., & Spinath, F. M. (2015). Intelligence and school grades: A meta-analysis. *Intelligence*, *53*, 118-137.

Rousselle, L. & Noël, M. P. (2007). Basic numerical skills in children with mathematics learning disabilities: A comparison of symbolic vs. non-symbolic number magnitude processing. *Cognition*, *102*, 361-395.

Rubinsten, O. & Sury, D. (2011). Processing ordinality and quantity: the case of developmental dyscalculia. *PloS one*, *6*, e24079.

Sasanguie, D., Defever, E., Maertens, B. & Reynvoet, B. (2014). The approximate number system is not predictive for symbolic number processing in kindergarteners. *The Quarterly Journal of Experimental Psychology*, *67*, 271-280.

Sasanguie, D., De Smedt, B., Defever, E., & Reynvoet, B. (2012). Association between basic numerical abilities and mathematics achievement. *British Journal of Developmental Psychology*, *30*, 344-357.

Sasanguie, D., De Smedt, B., & Reynvoet, B. (2017). Evidence for distinct magnitude systems for symbolic and non-symbolic number. *Psychological Research*, *81*, 231-242.

Sasanguie, D., Göbel, S. M., Moll, K., Smets, K., & Reynvoet, B. (2013). Approximate number sense, symbolic number processing, or number–space mappings: What underlies mathematics achievement? *Journal of Experimental Child Psychology*, *114*, 418-431.

Sasanguie, D., & Vos, H. (2018). About why there is a shift from cardinal to ordinal processing in the association with arithmetic between first and second grade. *Developmental Science, 21,* e12653.

Sattler, J. M., & Dumont, R. (2004). Assessment of children: WISC-IV and WPPSI-III supplement. San Diego: Jerome M. Sattler, Publisher.

Schiller, K. S., Khmelkov, V. T., & Wang, X. Q. (2002). Economic development and the effects of family characteristics on mathematics achievement. *Journal of Marriage and Family, 64*, 730–742.

Schneider, M., Beeres, K., Coban, L., Merz, S., Schmidt, S., Stricker, J. & De Smedt, B. (2016). Associations of non-symbolic and symbolic numerical magnitude processing with mathematical competence: a meta-analysis. *Developmental Science, 20, e12372.*

Schneider, M., Merz, S., Stricker, J., De Smedt, B., Torbeyns, J., Verschaffel, L., & Luwel, K. (2018). Associations of number line estimation with mathematical competence: A meta-analysis. *Child Development, 89,* 1467-1484.

Schneider, M., Thompson, C. A., & Rittle-Johnson, B. (2017). Associations of magnitude comparison and number line estimation with mathematical competence: A comparative review. In *Cognitive Development from a Strategy Perspective* (pp. 118-137). Routledge.

Schwarz, W., & Eiselt, A. K. (2009). The perception of temporal order along the mental number line. *Journal of Experimental Psychology: Human Perception and Performance*, *35*, 989-1004.

Seno, T., Taya, S., Ito, H., & Sunaga, S. (2011). The mental number line in depth revealed by vection. *Perception*, *40*, 1241-1244.

Siegler, R. S., & Booth, J. L. (2004). Development of numerical estimation in young children. *Child Development*, *75*, 428-444.

Siegler, R. S., & Lortie-Forgues, H. (2014). An integrative theory of numerical development. *Child Development Perspectives*, *8*, 144-150.

Siegler, R. S. & Opfer, J. E. (2003). The development of numerical estimation evidence for multiple representations of numerical quantity. *Psychological Science*, *14*, 237-250.

Siegler, R. S., & Ramani, G. B. (2009). Playing linear number board games—but not circular ones—improves low-income preschoolers' numerical understanding. *Journal of Educational Psychology*, *101*, 545.

Singer, V., & Strasser, K. (2017). The association between arithmetic and reading performance in school: A meta-analytic study. *School Psychology Quarterly, 32*, 435-448.

Sirin, S. R. (2005). Socioeconomic status and academic achievement: A meta-analytic review of research. *Review of Educational Research*, *75*, 417-453.

Skagerlund, K., & Träff, U. (2016). Processing of space, time, and number contributes to mathematical abilities above and beyond domain-general cognitive abilities. *Journal of Experimental Child Psychology*, *143*, 85-101.

Skagerlund, K., & Träff, U. (2014). Development of magnitude processing in children with developmental dyscalculia: space, time, and number. *Frontiers in Psychology*, *5*, 675.

Sokolowski, H. M., Fias, W., Ononye, C. B., & Ansari, D. (2017). Are numbers grounded in a general magnitude processing system? A functional neuroimaging meta-analysis. *Neuropsychologia*, *105*, 50-69.

Soltész, F., Szűcs, D. & Szűcs, L. (2010). Relationships between magnitude representation, counting and memory in 4-to 7-year-old children: A developmental study. *Behavioral and Brain Functions*, *6*, 1-14.

Soto-Calvo, E., Simmons, F. R., Willis, C., & Adams, A. M. (2015). Identifying the cognitive predictors of early counting and calculation skills: Evidence from a longitudinal study. *Journal of Experimental Child Psychology*, *140*, 16-37.

Spaepen, E., Gunderson, E. A., Gibson, D., Goldin-Meadow, S., & Levine, S. C. (2018). Meaning before order: Cardinal principle knowledge predicts improvement in understanding the successor principle and exact ordering. *Cognition*, *180*, 59-81.

Strenze, T. (2007). Intelligence and socioeconomic success: A meta-analytic review of longitudinal research. *Intelligence*, *35*, 401-426.

Szűcs, D., Devine, A., Soltész, F., Nobes, A., & Gabriel, F. (2013). Developmental dyscalculia is related to visuo-spatial memory and inhibition impairment. *Cortex*, *49*, 2674-2688.

Starkey, P. & Cooper, R. G. (1980). Perception of numbers by human infants. *Science*, *210*, 1033-1035.

Suanda, S. H., Tompson, W., & Brannon, E. M. (2008). Changes in the ability to detect ordinal numerical relationships between 9 and 11 months of age. *Infancy*, *13*, 308-337.

Szmalec, A., Loncke, M., Page, M., & Duyck, W. (2011). Order or disorder? Impaired Hebb learning in dyslexia. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*, 1270-1279.

Terrace, H. S., Son, L. K., & Brannon, E. M. (2003). Serial expertise of rhesus macaques. *Psychological Science*, *14*, 66-73.

Tillman, K., Tulagan, N., & Barner, D. (2015). Building the mental timeline: Spatial representations of time in preschoolers. *Proceedings of the 37th Annual Conference of the Cognitive Science Society.*

Tokyo International Communication Committee (2006). Japanese school system. Retrieved 7th September 2018 from: https://www.tokyo-icc.jp/guide_eng/educ/01.html

Torbeyns, J., Gilmore, C., & Verschaffel, L. (2015). The acquisition of preschool mathematical abilities: Theoretical, methodological and educational considerations. *Mathematical Thinking and Learning*, *17*, 99-115.

Träff, U., Desoete, A., & Passolunghi, M. C. (2017). Symbolic and non-symbolic number processing in children with developmental dyslexia. *Learning and Individual Differences*, *56*, 105-111.

Träff, U., & Passolunghi, M. C. (2015). Mathematical skills in children with dyslexia. *Learning and Individual Differences*, *40*, 108-114.

Tschentscher, N., & Hauk, O. (2014). How are things adding up? Neural differences between arithmetic operations are due to general problem solving strategies. *Neuroimage*, *92*, 369-380.

Turconi, E., & Seron, X. (2002). Dissociation between order and quantity meaning in a patient with Gerstmann syndrome. *Cortex*, 38, 911-914.

Vallar, G. (2007). Spatial neglect, Balint-Homes' and Gerstmann's syndrome, and other spatial disorders. *Cns Spectrums*, *12*, 527-536.

Van Atteveldt, N., & Ansari, D. (2014). How symbols transform brain function: A review in memory of Leo Blomert. *Trends in Neuroscience and Education*, *3*, 44-49.

Vanbinst, K., Ghesquiere, P., & De Smedt, B. (2012). Numerical magnitude representations and individual differences in children's arithmetic strategy use. *Mind, Brain, and Education*, *6*, 129-136.

Van Der Ven, S. H., Van Der Maas, H. L., Straatemeier, M., & Jansen, B. R. (2013). Visuospatial working memory and mathematical ability at different ages throughout primary school. *Learning and Individual Differences*, *27*, 182-192.

Van Dijck, J. P., Abrahamse, E. L., Acar, F., Ketels, B., & Fias, W. (2014). A working memory account of the interaction between numbers and spatial attention. *The Quarterly Journal of Experimental Psychology*, *67*, 1500-1513.

Van Dijck, J. P., Abrahamse, E. L., Majerus, S., & Fias, W. (2013). Spatial attention interacts with serial-order retrieval from verbal working memory. *Psychological Science*, *24*, 1854-1859.

Van Dijck, J. P., Gevers, W., & Fias, W. (2009). Numbers are associated with different types of spatial information depending on the task. *Cognition*, *113*, 248-253.

Van Dijck, J. P., & Fias, W. (2011). A working memory account for spatial–numerical associations. *Cognition*, *119*, 114-119.

Van Ewijk, R., & Sleegers, P. (2010). The effect of peer socioeconomic status on student achievement: A meta-analysis. *Educational Research Review*, *5*, 134-150.

Van Herwegen, J., Costa, H. M., Nicholson, B., & Donlan, C. (2018). Improving number abilities in low achieving preschoolers: Symbolic versus non-symbolic training programs. *Research in Developmental Disabilities*, *77*, 1-11.

Van Herwegen, J., Costa, H. M., & Passolunghi, M. C. (2017). Improving approximate number sense abilities in preschoolers: PLUS games. *School Psychology Quarterly*, *32*, 497-508.

Van Heuven, W. J., Mandera, P., Keuleers, E., & Brysbaert, M. (2014). SUBTLEX-UK: A new and improved word frequency database for British English. *The Quarterly Journal of Experimental Psychology*, *67*, 1176-1190.

Van Opstal, F., & Verguts, T. (2011). The origins of the numerical distance effect: the same–different task. *Journal of Cognitive Psychology*, *23*, 112-120.

Venkatraman, V., Ansari, D., & Chee, M. W. (2005). Neural correlates of symbolic and non-symbolic arithmetic. *Neuropsychologia*, *43*, 744-753.

Vincent, D., & Crumpler, M. (2007). Hodder Group Reading Tests 1–3 (II). *London: Hodder Education*.

Vogel, S. E., Goffin, C., & Ansari, D. (2015). Developmental specialization of the left parietal cortex for the semantic representation of Arabic numerals: an fMR-adaptation study. *Developmental Cognitive Neuroscience*, *12*, 61-73.

Vogel, S. E., Goffin, C., Bohnenberger, J., Koschutnig, K., Reishofer, G., Grabner, R. H., & Ansari, D. (2017). The left intraparietal sulcus adapts to symbolic number in both the visual and auditory modalities: Evidence from fMRI. *NeuroImage*, *153*, 16-27.

Vogel, S. E., Grabner, R. H., Schneider, M., Siegler, R. S., & Ansari, D. (2013). Overlapping and distinct brain regions involved in estimating the spatial position of numerical and non-numerical magnitudes: an fMRI study. *Neuropsychologia*, *51*, 979-989.

Vogel, S. E., Remark, A. & Ansari, D. (2015). Differential processing of symbolic numerical magnitude and order in first-grade children. *Journal of Experimental Child Psychology*, *129*, 26-39.

Von Aster, M. G., & Shalev, R. S. (2007). Number development and developmental dyscalculia. *Developmental Medicine and Child Neurology, 49*, 868–873.

Von Stumm, S., & Plomin, R. (2015). Socioeconomic status and the growth of intelligence from infancy through adolescence. *Intelligence*, *48*, 30-36.

Vos, H., Sasanguie, D., Gevers, W., & Reynvoet, B. (2017). The role of general and number-specific order processing in adults' arithmetic performance. *Journal of Cognitive Psychology*, 1-14.

Walsh, B. A., & Petty, K. (2007). Frequency of six early childhood education approaches: A 10-year content analysis of early childhood education journal. *Early Childhood Education Journal*, *34*, 301.

Walsh, V. (2003). A theory of magnitude: common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences*, *7*, 483-488.

Wang, L., Uhrig, L., Jarraya, B., & Dehaene, S. (2015). Representation of numerical and sequential patterns in macaque and human brains. *Current Biology*, *25*, 1966-1974.

Wechsler, D. (2003a). *Wechsler intelligence scale for children-WISC-IV*. Psychological Corporation.

Wechsler, D. (2003b) *Wechsler Preschool and Primary Scale of Intelligence – Third UK Edition (WPPSI-III)*. Oxford, England. Psychological Corp.

Wiese, H. (2007). The co-evolution of number concepts and counting words. *Lingua*, *117*, 758-772.

Williams, J. (2005). Mathematics assessment for learning and teaching. *London: Hodder Education*.

Wong, T. T. Y., Ho, C. S. H., & Tang, J. (2016). The relation between ANS and symbolic arithmetic skills: The mediating role of number-numerosity mappings. *Contemporary Educational Psychology*, *46*, 208-217.

Wylie, J., Jordan, J. A., & Mulhern, G. (2012). Strategic development in exact calculation: Group and individual differences in four achievement subtypes. *Journal of Experimental Child Psychology*, *113*, 112-130.

Xenidou-Dervou, I., Molenaar, D., Ansari, D., van der Schoot, M., & van Lieshout, E. C. (2017). Nonsymbolic and symbolic magnitude comparison skills as longitudinal predictors of mathematical achievement. *Learning and Instruction*, *50*, 1-13.

Xu, C., & LeFevre, J. A. (2016). Training young children on sequential relations among numbers and spatial decomposition: Differential transfer to number line and mental transformation tasks. *Developmental Psychology*, *52*, 854.

Xu, F., & Spelke, E. S. (2000). Large number discrimination in 6-month-old infants. *Cognition*, 74, B1-B11.

Yang, Y. (2003). Dimensions of socio-economic status and their relationship to mathematics and science achievement at individual and collective levels. *Scandinavian Journal of Educational Research*, 47, 21–41.

Yeniad, N., Malda, M., Mesman, J., van Ijzendoorn, M. H., & Pieper, S. (2013). Shifting ability predicts math and reading performance in children: A meta-analytical study. *Learning and Individual Differences*, *23*, 1-9.

Zampini, L., Suttora, C., D'Odorico, L., & Zanchi, P. (2013). Sequential reasoning and listening text comprehension in preschool children. *European Journal of Developmental Psychology*, *10*, 563-579.

Zampini, L., Zanchi, P., Suttora, C., Spinelli, M., Fasolo, M., & Salerni, N. (2017). Assessing sequential reasoning skills in typically developing children. *BPA-Applied Psychology Bulletin (Bollettino di Psicologia Applicata)*, *65*, 44-50.

Zorzi, M., Di Bono, M. G., & Fias, W. (2011). Distinct representations of numerical and non-numerical order in the human intraparietal sulcus revealed by multivariate pattern recognition. *NeuroImage*, *56*, 674-680.

Appendices

Appendix A: Order-Processing Questionnaire used in Study 1

Please circle the number which you feel best applies to your child for each question

My son/daughter:

Is easily confused by changes in routine

(1=very much disagree; 7=very much agree)

1----2----3----4----5----6----7

Understands how the seasons of the year follow each other (e.g. that autumn always comes after summer)

(1=very much disagree; 7=very much agree)

1----2----3----4----5----6----7

Can easily recall the order in which past events happened

(1=very much disagree; 7=very much agree)

1----2----3----4----5----6----7

Is able to plan a sequence of activities independently

(1=very much disagree; 7=very much agree)

1----2----3----4----5----6----7

Finds it difficult to learn new activities which involve a sequence of actions which have to be performed in a particular order (e.g., putting together the parts of a toy in the right order).

(1=very much disagree; 7=very much agree)

1----2----3----4----5----6----7

Would be able to recall the order of typical daily events.

(1=very much disagree; 7=very much agree)

1----2----3----4----5----6----7

Understands that some things always have to be done in a particular order

(e.g. putting on a school shirt before putting on a tie)

(1=very much disagree; 7=very much agree)

1----2----3----4----5----6----7

Finds it difficult to understand how the days of the week follow each other

(e.g. knowing that Wednesday comes after Tuesday)

(1=very much disagree; 7=very much agree)

1----2----3----4----5----6----7

Appendix B: Order-Processing Questionnaire used in Study 2

Please circle the number which you feel best applies to your child for each question.
My son/daughter:

Can easily adjust to changes in routine.
(1 = very much disagree; 7 = very much agree)
1----2----3----4----5----6----7

Understands how the calendar works.
(1 = very much disagree; 7 = very much agree)
1----2----3----4----5----6----7

Can easily recall the order in which past events happened.
(1 = very much disagree; 7 = very much agree)
1----2----3----4----5----6----7

Is able to plan a sequence of activities independently.
(1 = very much disagree; 7 = very much agree)
1----2----3----4----5----6----7

Finds it easy to learn new activities which involve a sequence of actions that have to be performed in a particular order (e.g., when learning to play computer or board games).
(1 = very much disagree; 7 = very much agree)
1----2----3----4----5----6----7

Would find it easy to remember a phone number.
(1 = very much disagree; 7 = very much agree)
1----2----3----4----5----6----7

Can organise their own time when doing certain tasks (e.g., can decide in what order to do different pieces of homework).

(1 = very much disagree; 7 = very much agree)

1----2----3----4----5----6----7

Appendix C: Zero-order correlations between T1 measures robustly related to maths at T1 and the components of the T1 maths measure

	Addition	Subtraction	Counting	Comparison
Deprivation	-.12	-.29**	-.15	-.19
Vocabulary	.13	.42**	.20	.18
OPQ	.14	.20	.23*	.27*
Number Ordering	.29**	.31**	.34**	.31**
Number Comparison	.17	.19	.05	.18
Daily Events	.38**	.42**	.27*	.29**
Counting	.41**	.35**	.39**	.48**
Order WM	.22*	.28**	.15	.29**

* $p < .05$, ** $p < .01$

Appendix D: Zero-order correlations between T1 measures robustly related to maths at T2 and the components of the T2 maths measure

	Counting & understanding number	Knowing & using number facts	Calculating	Measuring
Deprivation	-.28**	-.08	-.29**	-.28**
Vocabulary	.22*	.13	.30**	.41**
Block Design	.34**	.06	.25*	.18
OPQ	.17	.14	.21	.24*
Number Ordering	.39**	.22*	.19	.34**
Daily Events	.25*	.18	.37**	.44**
Non-Symbolic addition	.23*	.22*	.26*	.21
Number Comparison	.19	.22*	.15	.17
Counting	.39**	.28**	.25*	.34**

* $p < .05$, ** $p < .01$

Appendix E: Zero-order correlations between T2 measures robustly related to maths at T2 and the components of the T2 maths measure

	Counting & understanding number	Knowing & using number facts	Calculating	Measuring
Deprivation	-.28**	-.08	-.29**	-.28**
Vocabulary	.31**	.06	.26*	.41**
Block Design	.29**	.04	.24*	.17
OPQ	.17	.14	.21	.24*
Number ordering	.32**	.21*	.39**	.18
Counting	.52**	.41**	.42**	.29**
Non-symbolic addition	.38**	.19	.43**	.28**

* $p < .05$, ** $p < .01$

Appendix F: Initial and final models predicting arithmetic at the end of children's first year of school.

	β	t	p
Daily events	.43	4.08	< .001
Counting	.26	2.30	.024
Order Processing Questionnaire	.20	2.04	.044
Symbolic number ordering	.15	1.43	.158
Order WM	-.11	-.88	.381
Number comparison	-.03	-.33	.741
Daily events	.41	4.29	< .001
Counting	.24	2.46	.016
Order Processing Questionnaire	.21	2.31	.023

Initial model: $R^2 = .30$, $F(6, 84) = 7.05$, $p < .001$.

Final model: $R^2 = .31$, $F(3, 84) = 13.42$, $p < .001$.

Appendix G: Initial and final models predicting calculation scores at the end of children's second year of school from the measures at T1.

	β	*t*	*p*
Order Processing Questionnaire	.27	2.47	.016
Non-Symbolic addition	.24	2.22	.030
Daily events	.30	2.68	.009
Counting	.09	.78	.439
Symbolic Number Ordering	-.03	-.28	.778
Number Comparison	-.03	-.31	.761
Daily events	.32	3.11	.003
Order Processing Questionnaire	.26	2.61	.011
Non-symbolic addition	.22	2.16	.034

Initial model: $R^2 = .17$, $F(6, 81) = 3.70$, $p = .003$.

Final model: $R^2 = .19$, $F(3, 81) = 7.41$, $p < .001$.

Appendix H: Correlations between specific mathematics skills and the other measures in Study 2

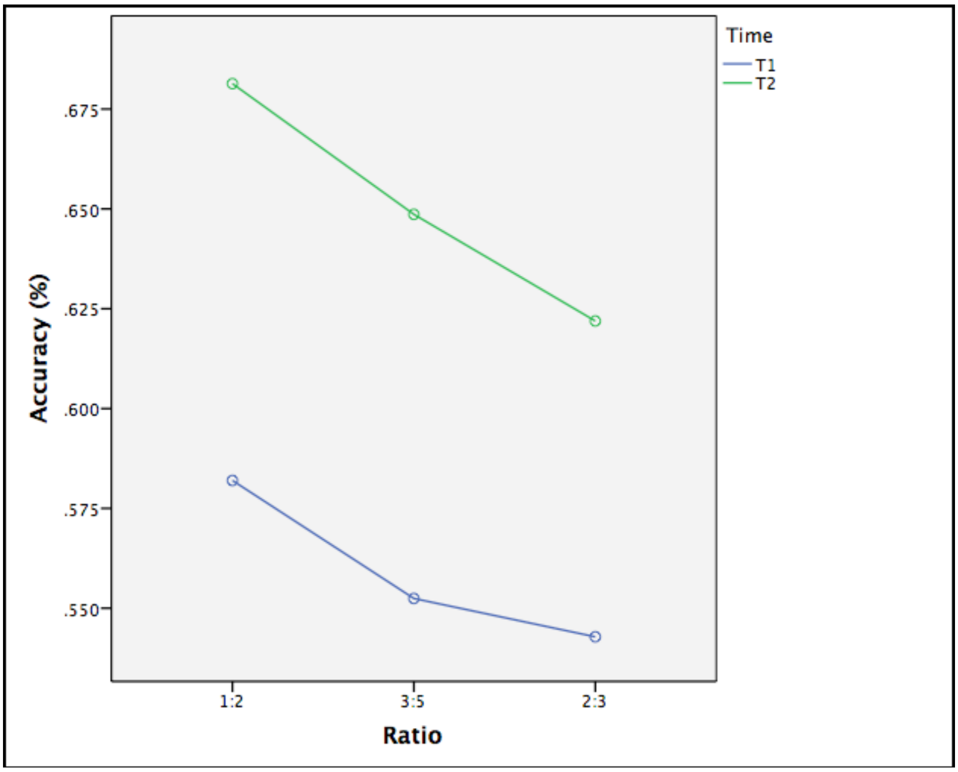
	Calculation	Measuring	Counting	Handling Data	Understanding Shape	Number Facts
MDM	-.05	-.08	<.001	.04	-.21*	-.16
Vocabulary	.22*	.32**	.44**	.38**	.34**	.45**
Block design	.14	.23*	.34**	.31**	.31**	.30**
Parental Questionnaire	.09	.19	.07	.24*	.08	-.04
Order WM	.31**	.31**	.33**	.30**	.47**	.51**
Visual-spatial WM	.17	.19	.14	.12	.04	.002
Number ordering	.37**	.33**	.37**	.22*	.24*	.29**
Event ordering	.21*	.21*	.23*	.18	.20*	.13
Number comparison	.35**	.27**	.33**	.17	.29**	.27**
Block comparison	.31**	.25*	.22*	.23*	.25*	.20
Number line	.30**	.37**	.50**	.28**	.24*	.29**
Stop signal	.10	.25*	.20*	.20*	.16	.09
Choice RT	.40**	.37**	.36**	.07	.17	.24*

Note: Higher scores on each task indicate better performance. [a] Performance on these tasks was indexed by a composite score created from accuracy and reaction times (the formula is described in the Method section). Task abbreviation: MDM: Multiple deprivation measure; OPQ: order processing questionnaire; WM: working memory; HGRT-II: Hodder Group Reading Test-second edition; MaLT: Mathematics assessment for Teaching and Learning Test. * $p < .05$, ** $p < .0$

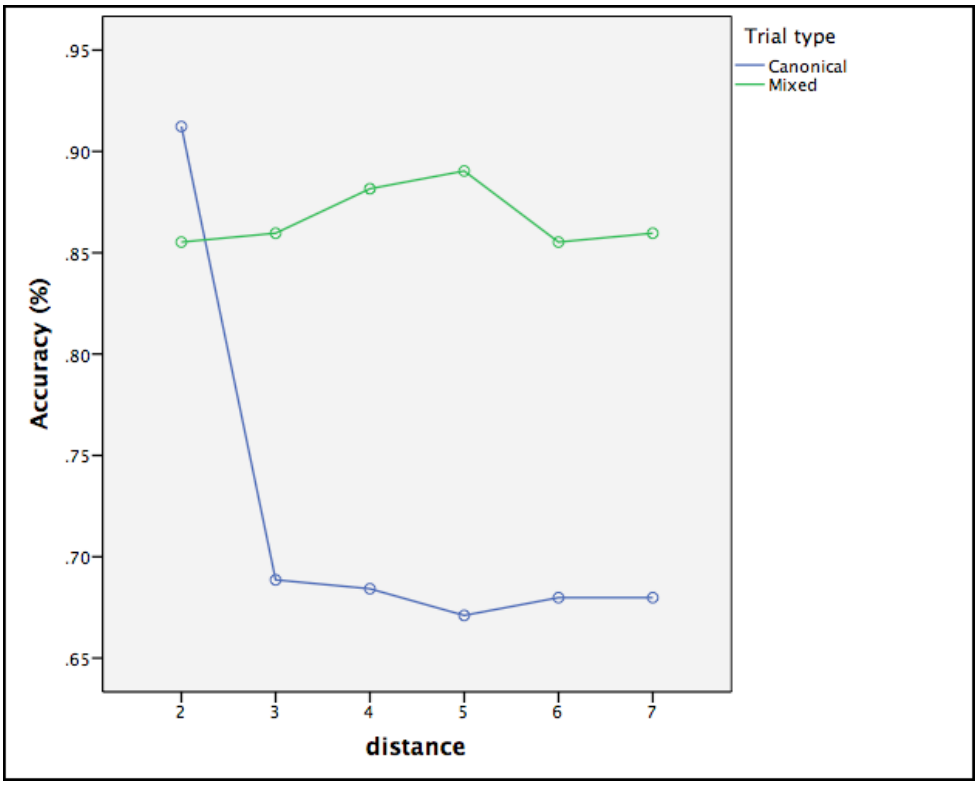
Appendix I: Correlations between task performance at T1 and maths achievement at T3 (O'Connor, Morsanyi & McCormack, in preparation)

Measure	*r*
Deprivation	-.44**
Vocabulary (raw score)	.52**
Block Design (raw score)	.50**
Order WM	.28*
Daily Events Accuracy	.41*
Number ordering	.25
Counting forward and backward	.44**
Non-symbolic addition	.14
Number Comparison	.23
Number Line task (Mean scaled error)	-.35**

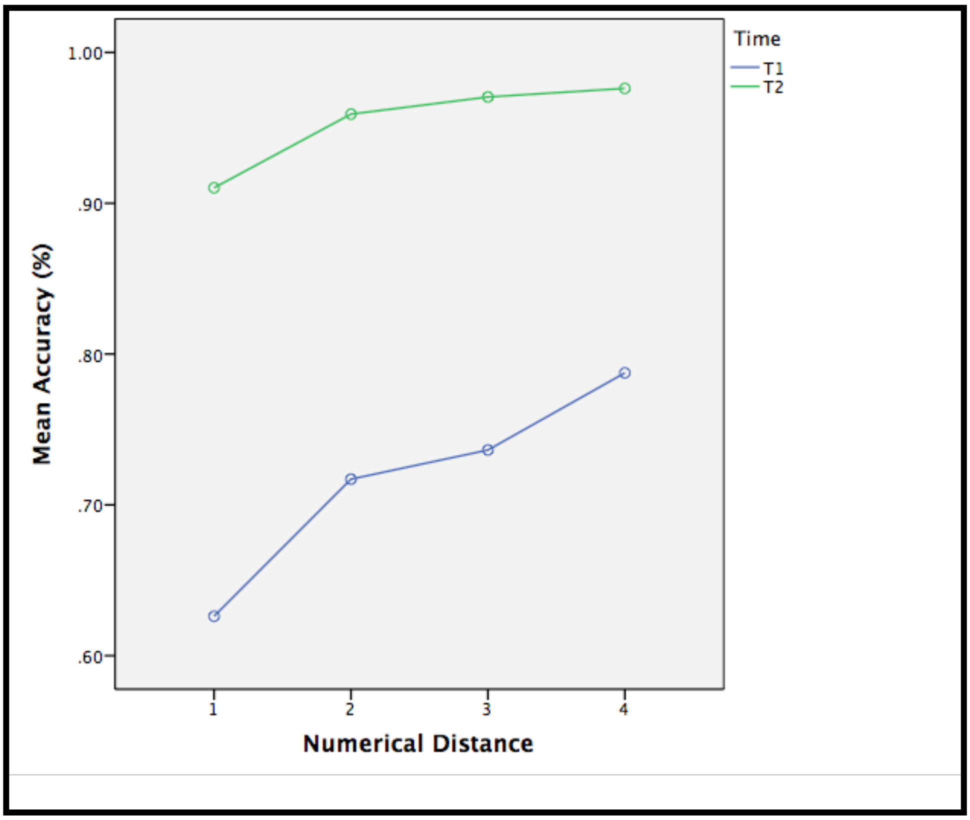
* $p < .05$, ** $p < .01$.



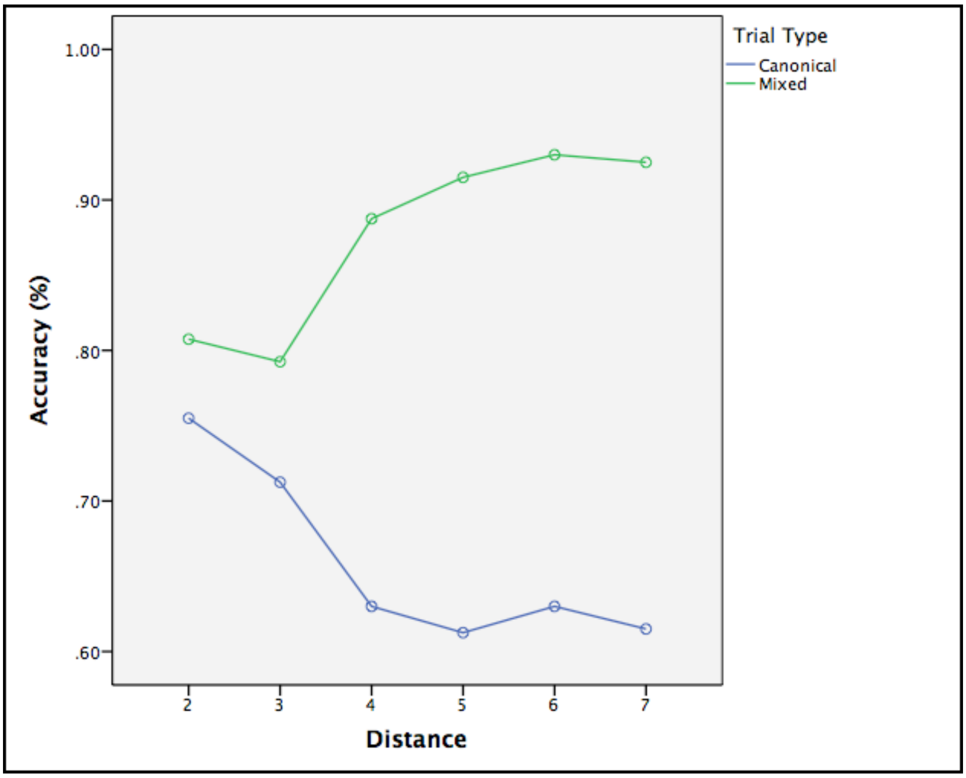
Appendix J: Graph showing ratio effects for the Non-symbolic addition task in Study 1. The ratio effect was non-significant at T1 ($p = .096$) but significant at T2 ($p = .011$).



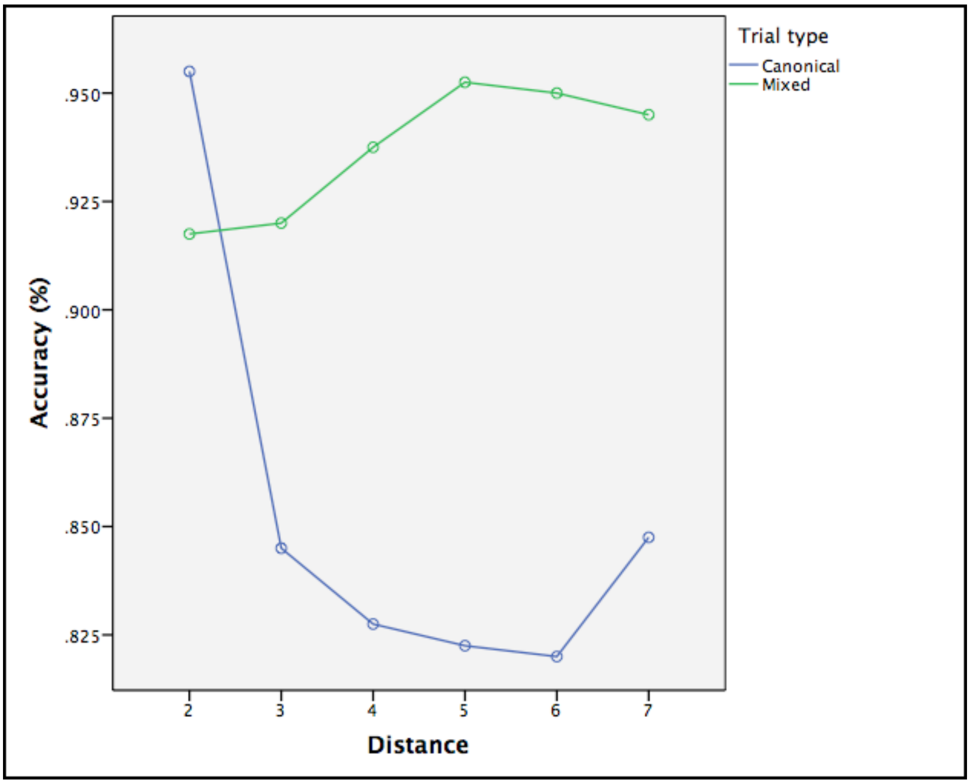
Appendix K: Graph showing the distance effects for canonical and mixed trials in the Ordinal judgement task at T2 in Study 1. There was a significant reverse distance effect for canonical trials ($p < .001$) but no significant distance effect for mixed trials ($p = .771$).



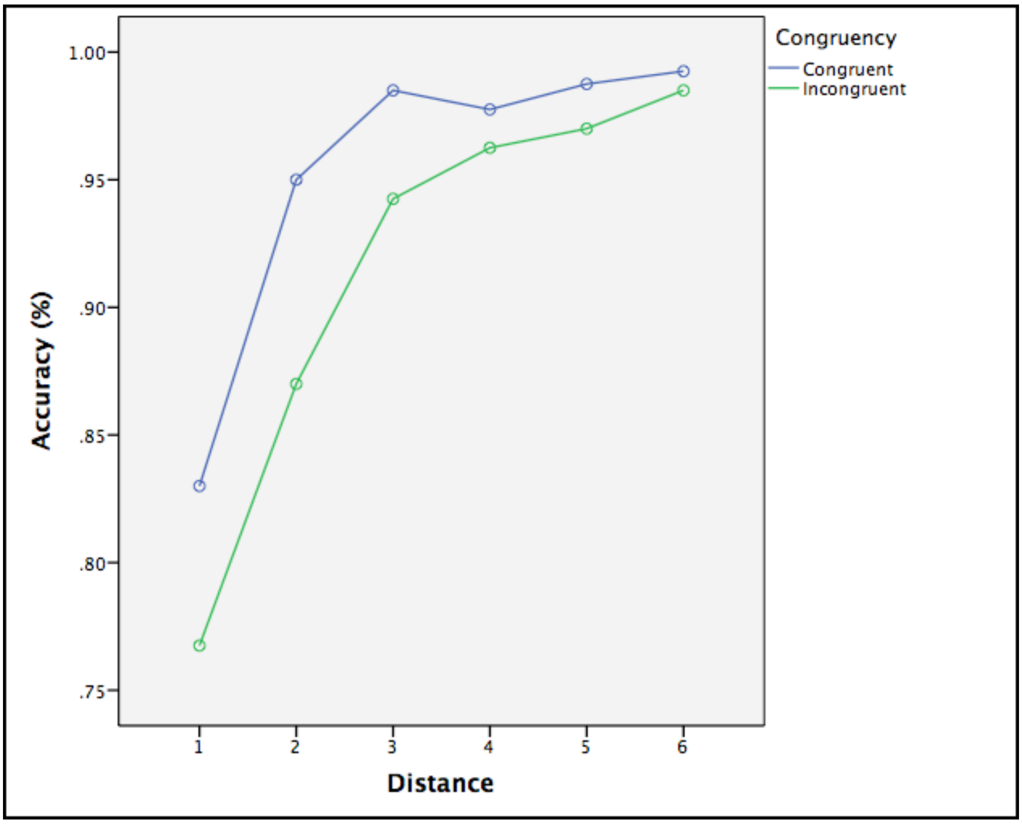
Appendix L: Graph showing distance effects for the Number comparison task in Study 1. The distance effect was significant both at T1 and T2 ($p < .001$).



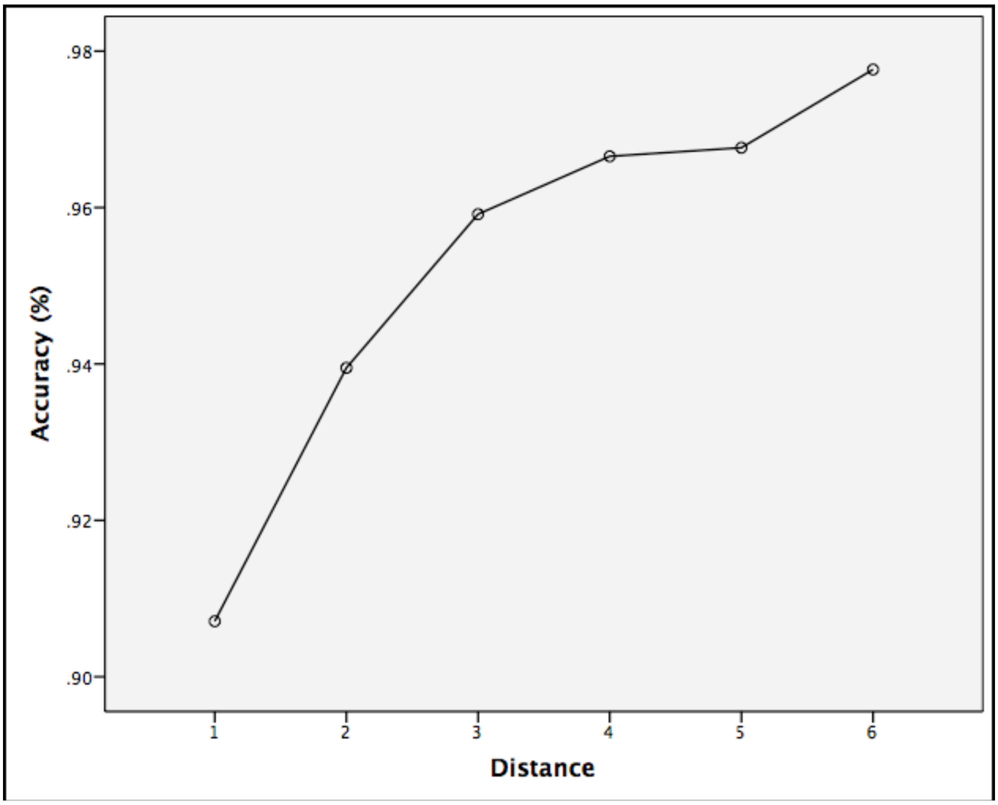
Appendix M: Graph showing the distance effects for canonical and mixed trials in the Ordinal judgement task in Study 2. There was a significant reverse distance effect for canonical trials ($p < .001$) but no significant distance effect for mixed trials ($p = .245$).



Appendix N: Graph showing the distance effects for canonical and mixed trials in the Annual events task in Study 2. There was a significant reverse distance effect for canonical trials ($p < .001$) and a significant distance effect for mixed trials ($p < .001$).



Appendix O: Graph showing the distance effects for congruent and incongruent trials in the Block comparison task in Study 2. There was a significant distance effect for congruent trials ($p < .001$) and for incongruent trials ($p < .001$).



Appendix P: Graph showing a significant distance effect ($p < .001$) for the Number comparison task in Study 2.

Appendix Q: O'Connor, P. A., Morsanyi, K. & McCormack, T. (2018). Young children's non-numerical ordering ability at the start of formal education longitudinally predicts their symbolic number skills and academic achievement in maths. *Developmental science*, e12645.

Appendix R: Morsanyi, K., van Bers, B. M., O'Connor, P. A., & McCormack, T. (2018). Developmental Dyscalculia is characterized by Order Processing Deficits: Evidence from Numerical and Non-Numerical Ordering Tasks. *Developmental Neuropsychology*, 43, 595-621.

Appendix S: O'Connor, P.A., Morsanyi, K. & McCormack, T. (2018). The stability of individual differences in basic mathematics-related skills in young children at the start of formal education. *Mind, Brain & Education.* Accepted - 28 Jan 2019

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PAPER

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Young children's non-numerical ordering ability at the start of formal education longitudinally predicts their symbolic number skills and academic achievement in maths

Patrick A. O'Connor | Kinga Morsanyi | Teresa McCormack

School of Psychology, Queen's University Belfast, Belfast, UK

Correspondence
Patrick A. O'Connor, Queen's University Belfast, School of Psychology, David Keir Building, Malone Road, Belfast, BT9 5AG, UK
Email: poconnor08@qub.ac.uk

Abstract

Ordinality is a fundamental feature of numbers and recent studies have highlighted the role that number ordering abilities play in mathematical development (e.g., Lyons et al., 2014), as well as mature mathematical performance (e.g., Lyons & Beilock, 2011). The current study tested the novel hypothesis that non-numerical ordering ability, as measured by the ordering of familiar sequences of events, also plays an important role in maths development. Ninety children were tested in their first school year and 87 were followed up at the end of their second school year, to test the hypothesis that ordinal processing, including the ordering of non-numerical materials, would be related to their maths skills both cross-sectionally and longitudinally. The results confirmed this hypothesis. Ordinal processing measures were significantly related to maths both cross-sectionally and longitudinally, and children's non-numerical ordering ability in their first year of school (as measured by order judgements for everyday events and the parents' report of their child's everyday ordering ability) was the strongest longitudinal predictor of maths one year later, when compared to several measures that are traditionally considered to be important predictors of early maths development. Children's everyday ordering ability, as reported by parents, also significantly predicted growth in formal maths ability between Year 1 and Year 2, although this was not the case for the event ordering task. The present study provides strong evidence that domain-general ordering abilities play an important role in the development of children's maths skills at the beginning of formal education.

RESEARCH HIGHLIGHTS

- Numerical and non-numerical ordering ability related to formal maths skills concurrently and longitudinally.
- Non-numerical ordering abilities in the first year of school were the strongest predictors of maths one year later.
- The study highlights the importance of domain-general ordering abilities to the early development of formal maths skills.

1 | INTRODUCTION

The relations between order processing abilities and the development of maths skills have recently attracted the interest of researchers. Lyons and Beilock (2011) proposed that representing and processing the relative order of numbers is a stepping stone in moving from approximate representations of number to exact representations. Separately, other researchers (e.g., Attout, Noël, & Majerus, 2014;

Attout & Majerus, 2015) have proposed that working memory for order information is important for early mathematics development.

Ordinality is a fundamental aspect of the symbolic number system, referring to the position in which a numeral is found within the number sequence. One proposal is that performance in tasks that tap children's ability to process symbolic order reflects the extent to which they have a refined spatialized representation of the number sequence along a mental number line (Kaufman, Vogel, Starke, Kremser, & Schocke, 2009). However, this suggestion does not explain why performance on non-numerical working memory tasks, which involve temporarily holding short non-numerical sequences in short-term memory, is related to maths abilities (Attout et al., 2014; Attout & Majerus, 2015). Existing findings suggest that the representation of the ordered number sequence in long-term memory and the ability to hold and process unfamiliar order information in short-term memory are both important for maths.

We believe that ordering skills and mathematics might be related for multiple reasons. Most relevant to young children is the fact that learning to count involves learning an ordered sequence of items. In addition, even the simplest counting principles (Gelman & Gallistel, 1978), such as the stable order principle (i.e., numerals always have the same order in a count), and the cardinal principle (i.e., the numeral applied to the last item in a set represents the number of items in the set) involve reference to ordinality. Nieder and Dehaene (2009) argue that it is difficult to envisage how children could acquire knowledge of the symbolic number system, beyond rote learning or other compensatory strategies, if they do not understand the correct order in which the numbers are arranged. Successful arithmetic performance is dependent upon both knowledge of the correct order of the numbers, and an understanding of the correct order in which mathematical operations should be carried out. For example, if children are asked to solve the problem "5 − 2 = ?", to arrive at the correct solution they must understand that they should take 2 away from 5, rather than vice versa. Thus, calculation itself depends upon temporarily holding order information in working memory. Processing order information is also essential for working with multi-digit numbers. It can be argued, therefore, that mental representations of order may play a role in the development of both basic symbolic number knowledge and subsequent maths ability, and recent evidence suggests that there is indeed a relationship between the processing of numerical order relations and maths achievement in both children and adults.

The most widely used task to assess symbolic ordering ability is the ordinal judgement task (e.g., Goffin & Ansari, 2016; Lyons & Beilock, 2011). Participants are shown three numbers on the screen (half of the pairs or triads are in the correct order, the other half are in the incorrect order) and they must judge whether the numbers are in the correct ascending order, from left to right. A task developed to assess non-numerical order processing skills is the order working memory (WM) task (e.g., Attout & Majerus, 2015). In this task, participants hear lists of familiar animal names. The lists range from two to seven animals in length, and participants must re-create the correct sequence of animals using cards that represent the animals in the list that they have just heard. Importantly, the cards given to participants inform them about both the identity and the number of animals within the list. Thus, the task makes minimal demands on item memory; participants must only remember the order of items. As will now be described, several studies have indicated that performance on both these types of order processing tasks is linked to maths ability, suggesting that both numerical and non-numerical ordering ability may be important for formal maths skills.

In a large study of children across school grades 1–6, Lyons, Price, Vaessen, Blomert, and Ansari (2014) investigated the role of basic number skills in the development of maths ability. The authors used a wide range of numerical and non-numerical tasks to investigate what skills were important for maths at different developmental stages. They found that the predictive power of numerical ordering ability (i.e., the ordinal judgement task) increased across grades. At the earliest grades, numerical ordering was not a strong predictor of maths, but by grade 6 (around the age of 12), it was the strongest of all the predictors. Another paper (Vogel, Remark, & Ansari, 2015) reported no relationship between distance effects in number ordering and first-graders' (around age 6–7) mathematics performance. However, Vogel et al.'s ordering task only contained dyads of numbers, rather than the triads that are more commonly used in this literature, and it is possible that the dyad task is less sensitive at detecting the appropriate order processing skills (although see Attout & Majerus, 2015). Overall, these studies suggest that symbolic ordering ability is important to children's maths skills, although the strength of this relationship might change with development.

Attout et al. (2014) investigated the links between verbal WM abilities (non-numerical item and order WM), numerical magnitude and order processing abilities and calculation performance at three different time points: 6 months into the final year of kindergarten (T1), one year later (T2) and during the second grade of school (T3). Attout et al. found that the only relationship between children's numerical ordinal judgement and maths was observed cross-sectionally at T2. On the other hand, children's performance in the order WM task was cross-sectionally related to maths at each time point, whilst performance on this task at T1 was longitudinally related to maths at T2 and T3, suggesting the importance of early non-numerical order memory to later maths performance. These relationships remained significant, even after controlling for age, verbal and non-verbal intelligence.

A relationship between order processing and maths has been found not only in studies involving typically developing children, but also in studies involving children with developmental dyscalculia (DD)—a developmental disorder characterized by difficulties in the retrieval and storage of arithmetic facts, when no other sensory or intellectual disabilities are present (e.g., Butterworth, 2005; von Aster & Shalev, 2007). Attout and Majerus (2015) investigated symbolic and non-symbolic magnitude and order processing in 8- to 12-year-old children with DD and a group of typically developing children matched on age, IQ and reading abilities. The children were given the order working memory task, as well as a calculation task, symbolic and non-symbolic ordinal judgement tasks (judging whether two sets of lines or numerals were in the correct ascending order numerically) and symbolic and non-symbolic magnitude judgement tasks (judging which of two sets of lines or numerals was the most numerous). Attout and Majerus found that the DD group tended to be slower on symbolic magnitude and ordering tasks and committed more recall errors in the order working memory task, suggesting that children with DD may have difficulties in processing and remembering order information.

Together, the evidence suggests that both numerical and non-numerical ordering abilities are important to the development of typical maths skills, and that children with DD have order processing deficits. Whilst the evidence is promising, there are still several important unresolved issues concerning the link between order processing skills and maths. In particular, we do not know the precise nature of the order processing skills that are important for maths development. Two quite distinct types of order processing tasks—the numerical ordinal judgement task and the order working memory task—have each shown a link with children's mathematical skills. Notably, Attout et al. (2014) found that children's performance on these two types of ordering tasks was not correlated (although see Attout & Majerus, 2015); performance on the tasks also showed quite different patterns of cross-sectional and longitudinal relations with maths skills. This suggests that they draw on different order processing skills and are related to maths skills for different reasons. Indeed, these tasks differ in two salient respects: (i) in terms of whether they involve processing of numerical or non-numerical order information and (ii) in terms of whether they involve retrieving and processing information from order representations held in long-term memory versus unfamiliar sequences temporarily held in short-term memory. Attout et al. (2014, p. 1676) suggest that "order WM abilities predict calculation abilities not via access to a common set of (long-term) ordinal representations but via mechanisms intrinsically associated with short-term storage capacities of order information". What is not clear is whether such short-term memory mechanisms are the only domain-general order processing ones that are important for maths development, because previous studies with children have not used tasks involving long-term ordinal representations of non-numerical information.

Lyons, Vogel, and Ansari (2016), in their review of the literature examining the links between ordinality and mathematical skills, argue that there is a paucity of research investigating the relation between non-numerical ordering abilities and maths. Recent studies with adults (Morsanyi, O'Mahony, & McCormack, 2017; Sasanguie, De Smedt & Reynvoet, 2017; Vos, Sasanguie, Gevers, & Reynvoet, 2017) showed that non-numerical order processing, as measured by month and letter ordering tasks that required participants to make judgements about the order of month/letter triads, was very strongly related to adults' numerical skills, and the distance effects found in these tasks were also similar to the distance effects found in number ordering tasks. Thus, the ordering of familiar non-numerical sequences is also related to maths ability, at least in adults. In order to investigate this issue developmentally, in the current study we included tasks that measured ordering ability involving familiar, non-numerical sequences.

We investigated the ability to process order information regarding familiar non-numerical sequences held in long-term memory by introducing two measures that have not been used previously. First, a temporal ordering task, inspired by previous research with young children (Friedman, 1977, 1990) was employed. The version of the task that we developed is similar to the number ordering tasks used in other studies (e.g., Lyons & Beilock, 2011; Lyons et al., 2014), except that children were shown a pictorial representation of a triad of daily events rather than numbers. Each test trial was drawn from a set of six events (waking up, getting dressed, going to school, eating lunch, eating dinner and going to bed) and children judged whether the order of the events was correct or not. Second, to assess the role of everyday non-numerical ordering skills, we developed a new eight-item questionnaire to assess the extent to which parents agreed or disagreed that their child could carry out familiar tasks that all included the requirement to follow a set order (such as getting dressed for school). Our motivation for using this measure was the existence of clinical reports of individuals with DD that describe how they often struggle with everyday tasks that have a strong ordering component (National Center for Learning Disabilities, 2007). Together, these tasks provided us with a novel way of assessing the relation between domain-general order processing abilities and emerging maths skills.

In addition to the question of what types of order processing skills are related to maths at the start of formal education, it is also of concern that there is a lack of longitudinal research investigating whether there may be a causal relationship between ordering ability and the early development of maths skills. This is echoed by Lyons et al. (2016), who point out that most of the findings concerning the link between ordering abilities and maths have been based on correlational evidence at a single time point. The only longitudinal study so far was conducted by Attout et al. (2014) who found separate cross-sectional links between both numerical ordering and non-numerical order working memory and maths, but only a longitudinal link between order working memory and maths. We employed a longitudinal design that involved children completing a range of tasks at the very start of their formal education, and then measuring their formal maths skills towards the end of their first and second year of school.

We studied children in their earliest years of education to address a further issue arising from the previous literature concerning the stage of development at which ordering ability becomes an important predictor of maths skills. Studies (e.g., Attout & Majerus, 2015; Lyons et al., 2014; Morsanyi, Devine, Nobes, & Szűcs, 2013) have consistently shown that order processing is strongly related to maths skills amongst older children (between the ages of 8 and 13). However, as mentioned above, there are mixed findings regarding whether there is a strong link between ordering abilities and maths at the start of formal education (Attout et al., 2014; Lyons et al., 2014; Vogel et al., 2015), with Lyons et al.'s (2014) finding that this relation only becomes pronounced with development. The children in the current study were between the ages of 4 and 5 when they first participated in the study, which makes them the youngest sample so far in which the link between order processing skills and maths ability has been investigated. It was conducted with a sample of children from Northern Ireland; Northern Ireland has the youngest school starting age (4 years old) of all the 37 countries participating in Eurydice, the information network on education in Europe (Eurydice at NFER, 2012), and one of the youngest school starting ages in the world.

Finally, it is also important to compare the predictive value of ordering tasks with other tasks that are related to mathematical skills (see e.g., Attout et al., 2014; Lyons et al., 2014; Vogel et al., 2015). Given the amount of research interest in whether the ability to process magnitudes is related to maths (e.g., Chen & Li, 2014; Gilmore, McCarthy, & Spelke, 2010; Halberda, Mazzocco & Feigenson, 2008; Holloway & Ansari, 2009; Piazza et al., 2010; Schneider et al., 2017), the current study included both symbolic and non-symbolic magnitude measures.

In sum, the aim of the current study was to assess the relative contributions of numerical and non-numerical order processing to the development of maths skills in children who have just begun formal maths instruction. In a longitudinal study, children were tested during their first year of primary school and completed a maths assessment at the end of the school year. The same children completed another maths assessment at the end of their second year of primary school. The main research question concerned whether numerical and non-numerical ordering abilities predicted variance in mathematical skills both cross-sectionally and longitudinally, after other powerful predictors of early mathematical skills, as well as children's verbal and non-verbal intelligence, were taken into account. In addition, the current study was the first to investigate the link between non-numerical ordering tasks including familiar and everyday sequences and maths performance at the start of formal education.

2 | METHOD

2.1 | Participants

Ninety children at the start of their first year of primary school education were recruited from four schools in the Belfast area (43 females, Mean age = 4 years 11 months; *SD* = 3.73 months). Eighty-seven children completed the maths assessment (43 females, Mean age = 6 years 2 months, *SD* = 3.44 months) at the end of their second school year. Due to the demographics of the population in Northern Ireland, the vast majority of children were of Caucasian origin; information on their SES is reported below.

2.2 | Materials

2.2.1 | Deprivation measure

Children's level of socioeconomic deprivation was determined using the Northern Ireland Multiple Deprivation Measure (Northern Ireland Statistics and Research Agency, 2010). This measure assigns a deprivation score to each electoral ward in Northern Ireland based on a variety of indices. A higher score indicates a higher level of deprivation for the area. The scores can be interpreted as percentiles (e.g., a score of 10 means that the area is less deprived than 90% of all postcode-based areas within Northern Ireland). In the current sample, deprivation scores ranged from 1.85 to 68.57 (Median = 11.00). One child did not provide a postcode, so a deprivation score could not be calculated. Along with age and both verbal and non-verbal intelligence, children's deprivation scores were used as covariates in the data analysis.

2.2.2 | IQ

Children's intelligence was measured using the Vocabulary and Block Design subtests of the Wechsler Preschool & Primary Scale of Intelligence – Third UK Edition (WPPSI-III UK; Wechsler, 2003). Children's estimated full-scale IQ scores were computed following the method outlined in Sattler and Dumont (2004) and were found to be within the normal range (Mean IQ score = 95.92, *SD* = 13.51).

2.2.3 | Order processing measures

Parental Order Processing Questionnaire (OPQ)

Parents were asked to complete an eight-item questionnaire (included in the Appendix) in which they indicated on a 7-point Likert scale the extent to which they agreed or disagreed with certain statements regarding their child's ability to perform everyday tasks that involved an order processing element (e.g., "my son/daughter can easily recall the order in which past events happened"). The items were developed based on clinical observations regarding the everyday difficulties that individuals with dyscalculia commonly encounter (National Center for Learning Disabilities, 2007), but they were modified to be appropriate for young children. Five items were scored positively (i.e., higher scores indicated better ordering ability), and three items were scored negatively. A principal component analysis with varimax rotation showed that the scale had a two-factor structure, with the positive items loading on factor 1 (which explained 41% of the variance), and the negative items loading on factor 2 (which explained 21% of the variance). The scale demonstrated good internal consistency (Cronbach's alpha = .75). The total score from this scale was used as a measure of children's ability to carry out everyday tasks requiring a long-term memory representation of the correct order of sequences. Five parents did not complete the questionnaire, so no score could be computed on this measure for their children.

Order working memory (WM) task

This task measured children's ability to retain serial order information. The English version was modelled on a task developed by Majerus and colleagues (Attout & Majerus, 2015; Attout et al., 2014; Majerus, Poncelet, Greffe, & Van der Linden, 2006). This task measures children's ability to retain and manipulate serial order information by measuring their ability to re-create the correct sequence of a list of animal names that were presented to them through a set of earphones, using cards depicting the animals. The stimuli used were seven monosyllabic English animal words (bear, bird, cat, dog, fish, horse, and sheep). The mean lexical frequencies of these words were established using SUBTLEX-UK word frequencies (SUBTLEX-UK: Van Heuven, Mandera, Keuleers, & Brysbaert, 2014). SUBTLEX-UK presents word frequencies as Zipf values, with values between 1 and 3 representing low frequency words and values between 4 and 7 representing high frequency words. The stimuli demonstrated high lexical frequency according to these values (mean lexical frequency = 4.94, range = 4.67–5.19). The stimuli were used to create 24 word lists, which ranged in length from two to seven words, with four trials per list length. Each word only appeared once per list and the same 24 lists were presented to all participants. The stimuli were recorded by a female voice, and an inter-stimulus interval of 650 ms was used. Mean item duration was 565 ms (range = 407–674 ms). For each correctly recalled sequence, children were given a score of 1. Split-half reliability estimates, using the Spearman-Brown formula, indicated good reliability (r = .93).

Daily events task

A modified version of Friedman's (1990) temporal ordering task was used to measure children's ability to judge the correctness of the order of familiar daily events. Children were first trained on how to order events using two training sequences (four cards showing a boy playing on a slide, and six cards depicting a sequence in which a boy picked up and opened a present). Children had to correctly order both sequences four times before they could proceed to the next phase of the training, which involved the items of the experimental sequence. The experimental sequence consisted of six cards that represented six familiar events that happen during the day (waking up, getting dressed, going to school, eating lunch, eating dinner and going to bed). For the training phase, children were first told what each picture represented and were shown the correct order by the experimenter. Then the cards were shuffled and children were asked to recreate the correct order. For the experimental sequence, children learned the names for each of the daily events and saw the correct order in which these events should go. After this, children were given a computer-based task in which they were told that they would see any three of the daily events and that their task was to judge whether the order was correct or not, from right to left, by pressing a tick or a cross on the touchscreen monitor. Half of the 24 trials (there were 12 sets that were presented twice) showed a triad of events in the correct order, the other half showed a triad that was in the incorrect order. Children were given a score of 1 for each correct answer and a measure of children's reaction times, for correct trials only, was also taken. Since each trial was presented twice, a split-half reliability was calculated using the Spearman-Brown coefficient, which was found to be adequate (.57). Due to the relatively high error rate, reliability for RTs for correct trials was not computed, and the RT measure was not considered further.

Symbolic number ordering[1]

This task assessed children's early knowledge of the order of symbolic numbers. Children were shown the correct sequence of the numbers 1–9 using cards. These cards were then shuffled and children were asked to re-create the correct forward order (involving two trials). This procedure was then repeated for the backward sequence of numbers (two trials). In two subtasks, children also ordered the numbers forwards (four trials) and backwards (four trials) from different starting positions, with a score of 1 given for each correct trial. The proportion of correct responses was calculated based on performance on all four of the ordering tasks. A reliability estimate for the total score was high (Cronbach's alpha = .93).

Counting

This task was based on the number sequence elaboration task, as outlined in Hannula and Lehtinen (2005). In the first part, children were asked to count from 1 until the highest number they could think of (they were stopped if they reached 50) in two trials. In two further subtasks, children also counted forwards and backwards from different starting points. Children could correct themselves once during any trial. The reliability estimate for both forward and backward subtasks combined was good (Cronbach's alpha = .77).

Given the strong correlation between counting until the highest number and both forward ($r(88) = .76$, $p < .001$) and backward counting ($r(88) = .65$, $p < .001$), a total counting score was calculated by adding z-scores for all three counting measures.

2.2.4 | Magnitude processing measures

Non-symbolic addition[2]

This task measured the ability to represent and manipulate non-symbolic quantities and was based on the procedure used by Gilmore et al. (2010), in which children view two sets of blue dots or "marbles" that a character had, which appear one after the other on the left-hand side of the screen, and have to estimate the sum of the two arrays (sum array) and compare that sum to the quantity of a third array (comparison array, composed of red dots) that a different character had, which appeared on the right-hand side of the screen. The numerical ratio of the sum and comparison arrays was manipulated across the 24 trials (1:2, 3:5, and 2:3), with eight trials per ratio. The number of dots for both arrays varied from 6 to 45; 6 being the lowest number of dots as this reduced the possibility that children could subitize the number of dots presented. Perceptual variables (dot size, density and array size) were also varied, so that they correlated with numerosity on half the trials (congruent trials) and were uncorrelated on the other half of the trials (incongruent trials), reducing the possibility that children may have used perceptual information as a cue when judging which array was the most numerous. Furthermore, the trials were designed in such a way that it was not possible for the children to perform above chance if they simply responded on the basis of a comparison between the number of blue dots in the second set and the number of red dots. In each trial the number of red dots was at least 1.5 times greater than the number of blue dots in the second set. Nevertheless, the overall number of blue dots was larger in half of the trials than the overall number of red dots, whereas in the other half of trials the opposite was true. In the task, children had to press one of two buttons on the touchscreen to indicate which character they thought had the most marbles. They completed four practice trials, with feedback given on their performance, followed by 24 experimental trials. Children were given a score of 1 if they correctly judged which character had the most marbles. Reliability for this task for accuracy was quite low, but acceptable (Cronbach's alpha = .50). One-sample t tests confirmed that children performed above chance at each ratio [1:2; $t(89) = 4.45$, $p < .001$. 3:5; $t(89) = 3.76$, $p < .001$. 2:3 $t(89) = 2.93$, $p < .001$].

Number comparison

Children's ability to compare symbolic quantities was assessed using a computer-based Number Comparison task (e.g., Dehaene, Dupoux, & Mehler, 1990) in which children were presented with a target number (between 1 and 4 or 6 and 9) and were asked to press one of two buttons to indicate whether they thought that the number on the screen was bigger or smaller than 5. Each number was presented five times, in a random order, giving a total of 40 experimental trials. These were preceded by four practice trials. Children were scored 1 for each trial in which they correctly judged whether the target number was bigger or smaller than 5, with reaction time data also obtained. Reliability estimates for accuracy (Cronbach's alpha = .88) and reaction times (Cronbach's alpha = .66) were good.

2.2.5 | Estimation measure

Number line task

The number line task (Cohen & Blanc-Goldhammer, 2011; Laski & Siegler, 2007, Link, Huber, Nuerk, & Moeller, 2014; Siegler & Opfer, 2003) was used to assess children's ability to spatially represent numbers along a mental number line. This task used the number-to-position version, in which children used their finger to indicate the position on the number line where a target number should go. This version used 1–10 and 1–20 scales, and it was framed as a game in which the children had to help Postman Pat to deliver presents to houses on different streets (Aagten-Murphy et al., 2015). There were six experimental trials, in which the child was asked to indicate the position of numbers 3, 4, 6, 7, 8 and 9. For the 1–10 number line, the numbers 5 and 10 were used as the two practice trials; for the 1–20 number line, the numbers 10 and 20 were used as the two practice trials, whilst the child was asked to indicate the position of the numbers 4, 6, 8, 13, 15 and 18 in the six experimental trials, which were presented in a random order. The number line was 1000 pixels long for both scales Children's error for each individual trial was calculated as the distance in pixels between children's estimated position and the actual position of the target number. The average of children's errors across both 1–10 and 1–20 scales was used as the overall measure of estimation error for the task. A reliability estimate was computed (Cronbach's alpha = .70).

2.2.6 | Maths achievement

At the end of their first year of school, children's maths ability was assessed by administering a 28-item maths achievement test, consisting of questions from the calculation subtest of the Woodcock-Johnson III tests of achievement (Woodcock, McGrew, & Mather, 2001) and from Form A of the Test of Early Mathematics Ability (TEMA-3; Ginsburg & Baroody, 2003). The questions from the calculation subtest contained six addition and four subtraction problems, whilst the questions from the TEMA-3 included the counting of objects and animals, selecting the next number after a given number in the counting list, as well as selecting which number is larger from a choice of two. At the end of their second year of school, children were assessed using the age-appropriate version of the Maths Assessment for Learning and Teaching (MALT; Williams, 2005) which consisted of 30 questions, assessing counting and understanding number (nine questions), knowing and using number facts (seven questions), calculating (eight questions) and measuring (six questions). Children's raw scores on both maths measures were used in the analyses. The reliability estimates for the maths measure at the end of children's first year of school (Cronbach's alpha = .91) and for the MALT at the end of children's second year (Cronbach's alpha = .83) were high.

2.3 | Procedure

The study received ethical approval from the university department's ethics committee. In Session 1, all children completed the Number Ordering task, followed by the Number Comparison task, the Animal Race task and finally, the Non-Symbolic Addition task. In Session 2, children completed the Daily Events Order task, followed by the WPPSI-III subtests, then the Baseline Reaction Time task, Counting task and then finally, the Number Line task. The computer-based tasks were designed using E-Prime Version 2.0. These tasks were presented on a touch screen, connected to a laptop. At the end of each school year (Time 1 = end of year 1; Time 2 = end of year 2), children completed the maths achievement test in small groups of 3–6, in which the experimenter read out the questions and instructed the children to write down their answers. All other tasks were administered individually.

3 | RESULTS

Descriptive statistics for both accuracy and reaction times are included in Table 1. The median number that children were able to count up to (out of 50) was 39. Most children performed well on the two numerical ordering tasks (forward and backward counting mean accuracy = 76%) and on number ordering (82%). Two children performed very poorly in these. In the non-numerical ordering tasks, children did not perform quite as well. In the daily events task, children's accuracy was 65%, which was above chance ($t(89) = 11.10$, $p < .001$). In the order working memory task, children on average got 9 trials correct, meaning that they were able to correctly remember ordered sequences to a sequence length of 3. Children's mean score on the OPQ was 44.02 out of 56, with parents tending to rate their children highly in terms of being able to carry out everyday tasks with a strong ordering component.

TABLE 1 Descriptive statistics for all measures

Measure	Minimum	Maximum	Mean *(SD)*
Vocabulary (scaled score)	4	17	8.52 *(2.10)*
Block Design (scaled score)	4	16	10.12 *(3.15)*
Order Processing Questionnaire	21	56	44.02 *(7.69)*
Order WM	1	16	9.52 *(4.54)*
Daily events accuracy	.38	1	.65 *(.13)*
Symbolic number ordering	0	1	.82 *(.30)*
Counting to 50	6	50	39 *(13.15)*
Counting forward and backward	0	1	.76 *(.22)*
Non-symbolic addition	.30	.88	.56 *(.11)*
Number comparison acc.	.40	1	.71 *(.19)*
Number comparison RT (ms)	778	6059	2404.04 *(1044.16)*
Number line task (Mean scaled error)	64	453	191.52 (74.90)
Baseline RT (ms)	860	2284	1435 *(283.71)*
Maths (Year 1)	1	28	23.24 *(4.88)*
Maths (Year 2)	7	29	21.74 (4.71)

As previously mentioned, children's accuracy on the non-symbolic addition task was relatively low, but their performance on the task was above chance ($t(89) = 5.09$, $p < .001$). Children performed much better on the number comparison task. In the number line task, children's estimates on the 1–10 scale were on average about 1.8 numbers away from the target number, whilst their estimates on the 1–20 number line were on average about 3.4 numbers from the target.

3.1 | Zero-order and partial correlations (after controlling for age, IQ and socioeconomic status) between the order and magnitude processing measures, counting ability and maths achievement at the end of children's first year of school

Table 2 shows that vocabulary scores were significantly positively correlated with order-processing (order WM, daily events, counting) and non-symbolic addition and maths scores. Block design scores were significantly positively correlated with the order-processing measures (order WM, daily events, number ordering), as well as performance on the number line task. Finally, higher deprivation scores were significantly related to lower performance on both IQ measures and maths, as well as lower performance on the order WM, daily events, number ordering and number comparison tasks.

As shown in Table 2, there were significant correlations between general order-processing measures and maths at the end of children's first year of school; children's maths ability was related to their scores on the OPQ, number ordering ability, daily events task accuracy, counting ability and their order working memory accuracy. Of the magnitude measures, only number comparison was found to be related to maths. After controlling for age, deprivation scores and verbal and nonverbal intelligence, number comparison performance was

TABLE 2 Zero-order correlations between all measures

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
(1) Age	–													
(2) Vocabulary	.04	–												
(3) Block Design	.09	.09	–											
(4) Deprivation	.11	−.41***	−.22*	–										
(5) Order Processing Q.	.08	.15	.03	−.09	–									
(6) Order WM	.17	.22*	.30**	−.22*	.18	–								
(7) Daily events	−.09	.38***	.29**	−.27**	−.08	.44***	–							
(8) Number ordering	.14	.19	.24*	−.23*	.26*	.41***	.24*	–						
(9) Counting	.09	.27**	.13	−.10	.15	.54***	.34**	.36**	–					
(10) Non-symbolic add.	−.23*	.24*	.12	−.19	−.14	.11	.22*	.19	.02	–				
(11) Number comparison	.06	.18	.09	−.22*	.20	.28**	.34**	.29**	.29**	.15	–			
(12) Number line (Error)	.21*	−.02	−.26*	.10	.11	−.05	−.15	−.05	−.20	−.14	−.04	–		
(13) Maths (Year 1)	−.004	.32**	.16	−.26*	.30**	.32**	.46***	.40***	.54***	.14	.21*	.02	–	
(14) Maths (Year 2)	.10	.37***	.29**	−.29**	.28*	.23*	.41***	.38***	.43**	.30**	.24*	−.17	.69***	–

Note. Task abbreviation: Add.: addition. Q: Questionnaire. WM: Working memory
$^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

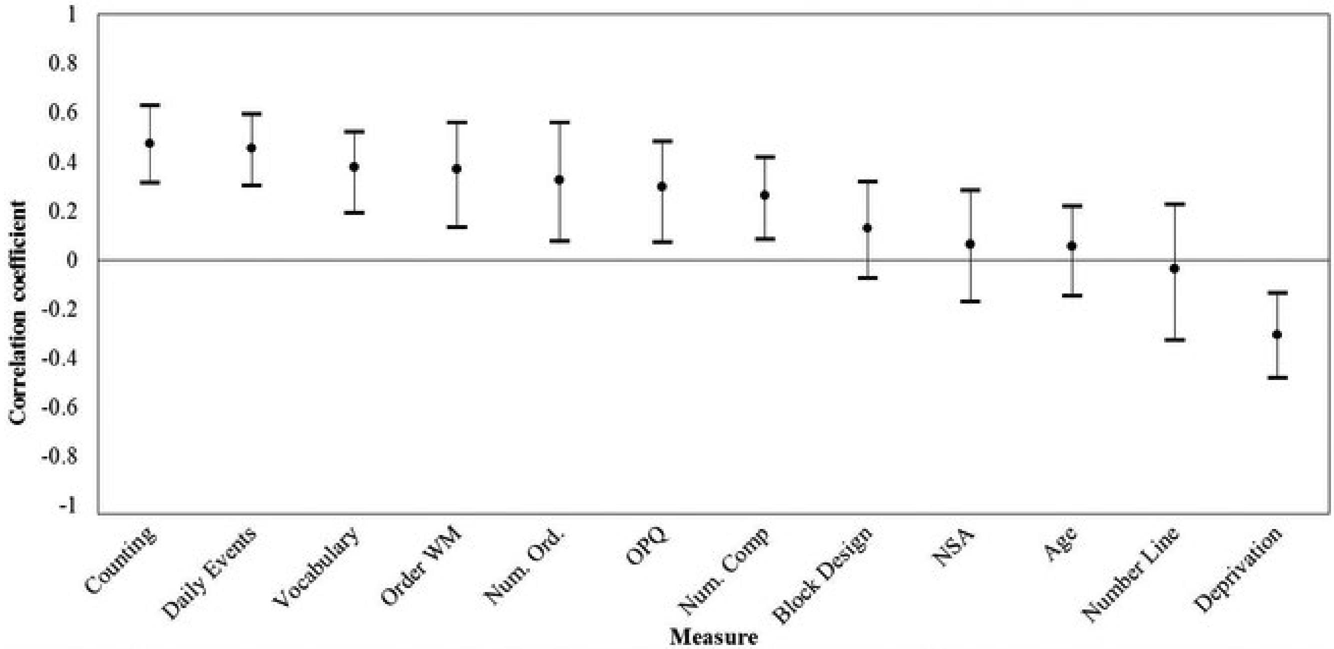

FIGURE 1 95% bootstrap confidence intervals for zero-order correlations between measures and maths achievement at the end of children's first year of school. Task abbreviations: NSA: Non-symbolic addition. Num. Comp.: Number comparison. Num. Ord.: Number ordering. OPQ: Parental Order Processing Questionnaire. WM: Working memory

no longer significantly related to maths performance (p = .29). OPQ scores, $r(78)$ = .26, p < .05; number ordering performance, $r(78)$ = .25, p < .05; daily events accuracy, $r(78)$ = .36, p < .01; counting ability, $r(78)$ = .43, p < .001; and order WM accuracy, $r(78)$ = .30, p < .01, remained significantly related to maths after controlling for the covariate measures.

3.2 | Zero-order and partial correlations between the order and magnitude processing measures, counting and maths achievement at the end of children's second year of school

Table 2 shows that vocabulary, block design and deprivation scores at T1 were significantly related to maths at T2. Children's T1 OPQ scores, daily events task accuracy, number ordering ability, order working memory accuracy, daily events accuracy and counting ability were related to maths ability at the end of children's second year of school. For the magnitude measures, both non-symbolic addition accuracy and number comparison accuracy were related to maths. After controlling for age, deprivation scores and verbal and non-verbal intelligence, the only significant relationships with maths were observed for OPQ scores, $r(75)$ = .24, p < .05; counting ability, $r(75)$ = .24, p < .05; and number ordering performance, $r(75)$ = .24, p < .05.

3.3 | Bootstrap correlations

A bootstrap procedure (using 10,000 samples) was also applied to assess the reliability of the relationship between the measures which had previously been observed as having a significant zero-order and/or partial correlation with maths, and maths achievement at each time point. This procedure allowed for a 95% confidence interval to be computed for the correlations between each measure and children's maths ability and if any measure was found to have a significant bootstrap correlation with maths, then it was considered to be robustly related to maths achievement. Figure 1 shows 95% bootstrap confidence intervals between the measures and maths achievement at the end of children's first year of school, whilst Figure 2 shows 95% bootstrap confidence intervals between measures and maths achievement at the end of children's second year of school.

Figure 1 shows that the measures which had previously shown significant zero-order and/or partial correlations with maths at the end of children's first year of school also showed significant zero-order bootstrap correlations with maths. Figure 2 shows that order working memory accuracy [r = .17, 95% CI (−.11, .41)] was the only measure that was not robustly related to maths at the longitudinal level, of all the measures that had previously been related to maths at the end of children's second year of school.[3]

3.4 | Regression modelling

The regression analyses regarding the relationship between the predictor variables and maths performance at each time point followed a similar procedure to that of Szűcs, Devine, Soltesz, Nobes, and Gabriel (2013). For each regression model, the variables that had a significant bootstrap correlation with maths were entered first. Non-significant predictors of maths in each model were then removed and each predictor which had a significant partial correlation with maths but not a significant bootstrap correlation was entered into the model one by

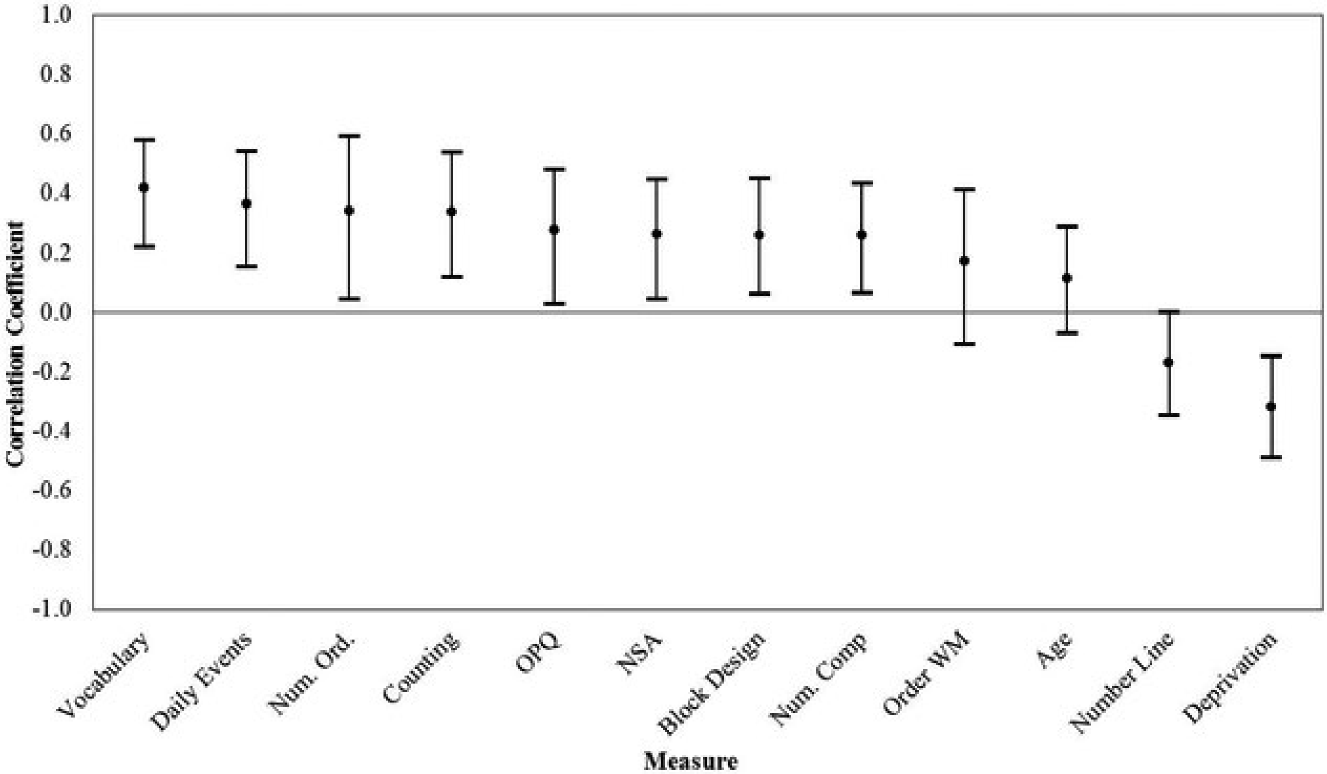

FIGURE 2 95% bootstrap confidence intervals for zero-order correlations between measures and maths achievement at the end of children's second year of school. Task abbreviations: NLT: Number line task. NSA: Non-symbolic addition. Num. Comp.: Number comparison. Num. Ord.: Number ordering. OPQ: Parental Order-Processing Questionnaire. WM: Working memory

one to examine whether they became significant. Then, the four covariates (age, deprivation scores, vocabulary and block design) were entered into the model to examine whether they changed significant predictors and improved fit. At each time-point, the model that explained the greatest proportion of variance with only significant predictors in the model was selected.

Table 3 shows the initial and final models for measures that predicted maths at the end of children's first year of school. The initial model consisted of OPQ scores, order WM, daily events, number ordering, counting and number comparison accuracy. This model explained 37% of the variance in maths scores; however, this model contained a number of non-significant predictors of maths (order WM; $\beta = -.07$, *ns*; number ordering; $\beta = .12$, *ns*; number comparison; $\beta = -.03$, *ns*). These measures were removed and only the significant predictors (OPQ scores, daily events and counting accuracy) were entered into the next model. When adding them to the model one by one, none of the remaining predictors explained significant additional variance in maths performance. Thus, this was accepted as the final model (see Table 3).

TABLE 3 Initial and final models predicting maths achievement at the end of children's first year of school

		β	*t*	*p*
Initial model	Daily events	.39	3.90	< .001
	Counting	.33	3.09	.003
	Order Processing Questionnaire	.27	2.89	.005
	Symbolic number ordering	.12	1.25	.214
	Order WM	−.07	−.65	.520
	Number comparison	−.03	−.31	.759
Final model	Daily events	.38	4.17	< .001
	Counting	.32	3.49	.001
	Order Processing Questionnaire	.28	3.23	.002

Initial model: $R^2 = .37$, $F(6, 84) = 9.33$, $p < .001$.
Final model: $R^2 = .39$, $F(3, 84) = 18.39$, $p < .001$.

Table 4 shows the initial and final models for the measures that significantly predicted maths at the end of children's second year of school. The initial model consisted of OPQ scores, daily events, number ordering, counting, non-symbolic addition and number comparison accuracy. This initial model explained 30% of the variance in children's maths scores at the end of their second year of school. The non-significant predictors (number ordering, counting and number comparison) were removed and the next model contained OPQ scores, daily events and non-symbolic addition accuracy, which explained 27% of the variance in maths performance. The two intelligence measures and deprivation scores did not explain significant additional variance in maths performance, although age was a significant factor when included in the model containing OPQ scores, daily events and non-symbolic addition accuracy, with this model explaining 30% of the variance in children's maths performance at the end of their second year of school.[4]

TABLE 4 Initial and final regression models predicting maths achievement at the end of children's second year of school

		β	t	p
Initial model	Order Processing Questionnaire	.28	2.77	.007
	Non-symbolic addition	.26	2.60	.011
	Daily events	.25	2.38	.020
	Counting	.19	1.80	.075
	Symbolic number ordering	.11	1.07	.289
	Number comparison	.04	.35	.728
Final model	Daily events	.35	3.67	< .001
	Order Processing Questionnaire	.32	3.36	.001
	Non-symbolic addition	.30	3.04	.003
	Age	.20	2.06	.042

Initial model: R^2 = .30, F(6, 81) = 6.71, p < .001.
Final model: R^2 = .30, F(4, 81) = 9.53, p < .001.

As a final step, we checked whether the longitudinal predictors of formal maths skills at the end of the second year of school also remained significant if the effect of formal maths skills at the end of the first school year were taken into account. We did this by adding formal maths skills at T1 as a predictor to the final regression model presented in Table 4. This analysis addressed the question of whether these longitudinal predictors of maths also predicted growth in maths skills during the second year of school. The model is presented in Table 5. This model explained 41% of the variance in T2 formal maths skills with formal maths skills at T1, the order processing questionnaire and non-symbolic addition as significant predictors. The effect of the daily event ordering task was no longer significant, and the effect of age was also reduced to a non-significant trend.

4 | DISCUSSION

Children's ability to process both numerical order (counting, number ordering) and non-numerical order (OPQ, daily events and order working memory) at the start of their first school year were robustly related to their maths achievement at the end of their first year. These relationships were significant, even after controlling for age, deprivation scores and verbal and nonverbal intelligence. Multiple regression analyses revealed that, after controlling for the effect of counting ability (forwards and backwards), the order processing questionnaire and the daily events task still remained significant predictors of maths ability. The longitudinal analysis (i.e., predicting maths performance at the end of the second school year) showed that children's numerical ordering ability (counting forwards and backwards and symbolic number ordering) at the start of formal education was robustly related to their maths achievement at the end of their second year of school. Scores on the OPQ and daily events task accuracy were also robustly related to maths at the longitudinal level. The regression analyses revealed that early non-numerical ordering abilities (OPQ scores and daily events task accuracy) were significant predictors of children's maths achievement more than 1 year later even when the significant effects of counting ability, and non-symbolic addition were controlled. When the effect of T1 formal maths skills was controlled, only the OPQ and the non-symbolic addition task explained additional variance in T2 formal maths skills, whereas the effect of the daily events task was no longer significant. This suggests that the effect of the daily events task was the strongest during the first school year, and it related to maths abilities in the second year of school via its links with early formal maths skills. By contrast, everyday order processing abilities remained significantly related to formal maths skills throughout the first two years of school.

These results strongly support the notion that ordinality is important to the development of early maths skills (e.g., Attout & Majerus, 2015; Attout et al., 2014; Lyons et al., 2014). Our detailed analyses of the components of the formal maths tests also showed that ordinality was important to all aspects of maths, including counting, calculation, and the understanding of number facts and measures. Our results also extend previous findings by showing that, even at the very earliest stages of formal schooling, children's domain-general ability to process order, as demonstrated in familiar everyday tasks and to a lesser extent, their ability to order daily events, plays an important role in the successful development of more mature maths skills. This extends work with adults (Morsanyi et al., 2017; Sasanguie et al., 2017; Vos et al., 2017) that showed strong relationships between non-numerical ordering tasks and mathematics abilities. The domain-general ability to use order information measured by the daily events task must be based on long-term memory representations of familiar sequences, and our findings indicate that it is distinct from the ability to process ordinal information held in short-term memory. Indeed, while we replicated Attout et al.'s (2014) findings of a concurrent relation between non-numerical order WM and children's maths skills, performance on the OPQ and the daily events task were in fact better predictors of maths skills both concurrently and longitudinally.

Our results are novel in suggesting that there are two distinct domain-general ordering abilities that support maths development. Attout et al. (2014) show that the ability to hold ordered unfamiliar sequences in working memory is important, and make a strong case for why such an ability may be crucial for calculation abilities. In addition,

TABLE 5 Regression model predicting formal maths achievement at the end of children's second year of school taking into account the effect of formal maths achievement at the end of the first school year

	β	t	p
T1 maths	.41	3.92	<.001
Daily events	.16	1.62	.109
Order Processing Questionnaire	.19	2.03	.045
Non-symbolic addition	.26	2.93	.004
Age	.17	1.95	.054

R^2 = .41, F(5, 81) = 12.13, p < .001.

our results indicate that representing and processing familiar ordered sequences in long-term memory may be fundamental for the emergence of very early maths skills, when children are learning to represent and use numbers as an intrinsically ordinal sequence. The idea that such domain-general abilities underpin early maths skills is consistent with Rubinsten and Sury's (2011) claim that processing order information forms part of the cognitive foundations of mathematics.

Such a domain-general ability is likely to be in operation well before children learn mathematics, and indeed a considerable body of research indicates that children rapidly acquire representations of repeated event sequences over multiple time scales during the preschool years (Fivush & Hammond, 1990; Nelson 1986, 1998). Acquiring and using ordered representations of repeated events forms a crucial part of children's learning about the world, and indeed has been argued to be foundational in cognitive development (Nelson, 1998). Our findings provide the first evidence that suggests that the same processes also support emerging maths abilities.

One important and unresolved issue, though, is whether there is a domain-general representational format for representing ordered information in long-term memory, and specifically whether such representations are spatial in nature. Our data do not allow us to answer this question, but we note that Friedman (1977, 1990) has argued that 4- to 5-year-olds have spatialized representations of familiar events (and, indeed, our daily event ordering task and our number ordering task required children to understand the mapping of temporal order to spatial order; although see Tillman, Tulagan, & Barner, 2015, for evidence that 4-year-olds do not do this mapping spontaneously). Friedman and Brudos (1988) claimed that 4-year-olds use a common representational system for coding both spatial and temporal order information, raising the possibility that the ability to represent items in this way is then utilized in the context of mathematics as well. Such an idea is broadly consistent with other claims regarding the way temporal order and numbers are represented (e.g., see Bonato, Zorzi, & Umiltà, 2012, for review of research on the "mental time line" and "mental number line"). We note that Berteletti, Lucangeli, and Zorzi (2012) have made what could be interpreted as a contrasting claim, namely that children's conception of numerical order develops first and is then generalized to other non-numerical sequences. It is important to point out that the non-numerical sequences that they studied are those acquired later than the number sequence during formal education (the alphabet and months of the year), rather than familiar event sequences which are acquired very early in development. Moreover, the issue that Berteletti et al. are concerned with is whether the items in sequences in question are spaced linearly (by contrast to log spacing), rather than the more basic issue of whether they share a spatialized representational format. We note that children's performance on our number line task did not relate to performance either on the daily event task or on the OPQ, nor even on the number ordering task, suggesting that the precision of children's placing of numbers on a line measures something different from the ability to represent and process either numerical or non-numerical ordinal information.

Despite focused research on this issue, there is much that is not yet known about the commonalities between temporal, numerical, and spatial representation; we would suggest that our findings provide new impetus for considering such commonalities, particularly those between time (understood here as event order) and number, and how such commonalities may play a role in the acquisition of maths skills.

Another important contribution of the current work is that it provided the first evidence for a link between parentally reported everyday ordering abilities and formal maths skills. Whereas clinical observations of individuals with developmental dyscalculia have described everyday order processing difficulties, this study was the first to show that this link is also present in the case of a sample of young, typically developing children. Indeed, the OPQ longitudinally predicted growth in formal maths skills during the second year of school. This finding could have great practical importance, as it offers the possibility to screen children for vulnerability to develop mathematics difficulties even before they start their formal education. Indeed, our questionnaire was designed for 4-year-old children; in many countries, this would be 2–3 years before the children start their formal education in maths. The questionnaire that we developed to measure children's everyday order processing abilities had good psychometric properties, and it only took a few minutes to complete, which makes it very convenient to use. Nevertheless, future work could further improve the psychometric properties and the predictive value of this questionnaire.

Our study examined a number of other predictors of maths skills used in previous studies. As we have pointed out, we replicated Attout et al.'s (2014) finding that order WM was related to maths skills in the first year of school, but in our sample, order working memory at the start of formal schooling did not longitudinally predict maths performance at the end of the second year of schooling. Regarding other predictors of maths performance, Lyons et al. (2014) found that number comparison and number line performance were the best predictors of maths performance in the first school year. We also found a robust relationship between number comparison performance and maths skills both at the cross-sectional and longitudinal levels, which is also in line with several other studies that showed a strong relationship between number comparison and maths skills at the start of formal education (e.g., Attout et al., 2014; Holloway & Ansari, 2009; Mundy & Gilmore, 2009; Rousselle & Noël, 2007). Given the well-established link between this task and maths ability, and the fact that it involves symbolic number processing, it is striking, though, that number comparison did not explain additional variance in maths skills, once the effect of counting skills and everyday ordering abilities were controlled.

Regarding number line performance, several studies found a reliable relationship between this task and maths achievement in children from as young as 3 years old (e.g., Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Booth & Siegler; 2006, 2008; Link et al., 2014; Siegler & Booth, 2004). Studies typically use a paper-and-pencil version of this task, and it is possible that the link between maths skills and performance on the number line task would have been stronger had we used the typical presentation format. Nevertheless, the task showed good reliability, and children's estimations were not very far from the correct positions of target numbers. Performance on this task was also related to children's block design scores, which supports the validity of the tasks. There was also a non-significant trend (p = .118) toward a relationship between number line performance and formal maths skills at T2.

Number ordering performance was significantly related to math abilities both in Year 1 and Year 2. Nevertheless, surprisingly, non-numerical ordering tasks were more strongly related to maths abilities than number ordering. This raises the question of whether our version of the task was ideally suited to measure number ordering skills. As we noted earlier, other researchers used computer-based verification tasks to measure number ordering skills in young children (e.g., Lyons et al., 2014) that were analogous to our daily events task, albeit involving numbers. However, in a pilot test, our participants found this version of the task too challenging, possibly because they were younger than the participants in all the other studies. Some researchers (e.g., Attout & Majerus, 2015; Attout et al., 2014; Vogel et al., 2015) presented children with dyads of numbers rather than triads in their number ordering task. The dyad version was successfully performed by children as young as 5–6 years old (Attout et al., 2014). However, an issue with this version of the task is that Vogel et al. (2015) reported no reverse distance effects on the task, which have been consistently found by researchers who used number triads in their ordering task. Thus, it is possible that the two versions of the number ordering task (i.e., using dyads vs. triads) do not rely on exactly the same cognitive processes. In particular, it is less certain that participants must rely on order information per se in the dyad task than in the triad task. For these reasons, we employed a production version of the number ordering task.

We believe that this task was appropriate for our sample, given that we found stronger correlations between number ordering and maths skills than other researchers who looked at this relationship in the case of young children (e.g., Attout et al., 2014; Lyons et al., 2014; Vogel et al., 2015). Indeed, the typical finding in the case of young children is a weak/non-significant relationship.[5] By contrast, we found that number ordering was significantly related to all aspects of maths at both T1 and T2. Furthermore, we found a moderate relationship between the daily events task and the number ordering task, suggesting that both tasks were assessing some of the same skills. Regarding the predictive value of production vs. verification tasks, whilst we did not use the verification version of the number ordering task, our number comparison task was a verification task. Although children performed better on that task than on the daily events task (i.e., a verification task that measured ordering ability), performance on the number comparison task was less strongly related to maths than the daily events task at both T1 and T2.

There is evidence that, as children get older, number ordering skills become increasingly strongly related to maths abilities (see Lyons et al., 2014). Regarding non-numerical ordering skills, the developmental pattern of their links with maths abilities has not been investigated so far. Some recent studies (e.g., Morsanyi et al., 2017, Sasanguie et al., 2017; Vos et al., 2017) have demonstrated that non-numerical ordering skills remain strongly related to arithmetic skills even in the case of adults, although these links are not quite as strong as the relations between numerical ordering skills and maths. Thus, it is plausible to assume that at some point in development (most likely during the first years of school) number ordering skills become more strongly related to maths skills than non-numerical ordering. Nevertheless, this question requires further investigation.

Non-symbolic addition performance was a significant predictor of children's later maths achievement, and growth in formal maths skills during the second year of school, although it was not related to maths performance at the end of the first school year. The task was designed in such a way that children could not perform above chance if they only relied on simple perceptual strategies (see Gilmore et al., 2010; Rousselle & Noël, 2007; Soltész, Szűcs, & Szűcs, 2010). Unsurprisingly, young children found this task difficult. Whereas the finding that performance on this task predicted maths performance is in line with studies that found a link between non-symbolic estimation skills and mathematics performance (see Chen & Li, 2014, for a meta-analysis), it is important to note that the non-symbolic addition task has further cognitive requirements, including memory, spatial attention and inhibition, which are also important for maths development.

Indeed, one limitation of the current study is that it did not consider some domain-general factors that are likely to play a role in numerical development. Although IQ and order working memory were measured in the current study, other general cognitive skills were not considered. There is much evidence to suggest that other aspects of working memory processes (Passolunghi, Cargnelutti & Pastore, 2014; Passolunghi, Vercelloni, & Shadee, 2007; Szűcs et al., 2013; Van der Ven, Van der Maas, Straatemeier, & Jansen, 2013) and executive functions (Gilmore et al., 2013; Passolunghi & Siegel, 2001; Soltész et al., 2010; Szűcs et al., 2013) are related to maths. In particular, it would be interesting to investigate verbal and spatial working memory and inhibition skills together with the ordering tasks, as these skills might play a role in ordering performance (e.g., van Dijck, Abrahamse, Majerus, & Fias, 2013; van Dijck & Fias, 2011; Morsanyi et al., 2017).

Another limitation that could be noted is that formal maths skills were not assessed at the start of the first school year. Indeed, although we used a broad range of tasks to measure basic maths abilities (including non-symbolic measures, counting skills, and measures that required the knowledge of symbolic numbers, such as the number line task, and the number ordering task), it is possible that children had already possessed some of the formal maths skills (e.g., addition and subtraction) that were assessed at the end of the first school year. Thus, although our findings demonstrated that early, non-numerical ordering skills were strongly related to formal maths skills at the end of the first school year, it is unclear whether early ordering abilities predicted growth in formal math abilities during the first school year. This question might be explored in future studies.

Finally, we have already discussed the possibility of using everyday ordering abilities as early indicators of potential vulnerability to maths difficulties in young children. Another possible future direction is to develop non-numerical training exercises that could be used to help young children to improve their ordering abilities. One interesting question is whether the effects of training in non-numerical ordering might generalize to number ordering skills, and numerical skills in general. In fact, there is a possibility that ordering skills might play an important role in the development of other academic skills as well, as Perez, Majerus, and Poncelet (2012) found that order WM capacity longitudinally predicted reading development in the case of young children. The same authors (Perez, Majerus, & Poncelet, 2013) also reported that adults with dyslexia displayed a deficit in order WM. It is possible that the link between domain-general order processing and other academic skills is specific to short-term memory mechanisms, but our findings suggest that it might be useful to examine whether such a link also extends to the sort of ordering processing skills measured in our study.

In conclusion, the current study has shown that children's ability to process order, at the earliest stage of formal schooling, is an important predictor of maths achievement concurrently and 1 year later. In particular, it seems that non-numerical ordering ability (for familiar tasks and daily events) is a stronger predictor of children's maths ability than numerical order at the early stages of education. Although on the basis of the current findings it is not possible to establish whether early non-numerical ordering abilities predict growth in formal maths skills during the first school year, such evidence was found in the second year of school, at least in the case of the parental report of children's ordering skills. General ordering ability may be a suitable target for intervention for young children, and measuring ordering ability could potentially be used to identify children who are at risk of developing maths difficulties, even before they start formal education.

ENDNOTES

[1] The typical task in the literature that is used to measure number ordering ability is a computer-based task in which children are shown dyads or triads of numbers and have to judge whether the order is correct or incorrect/ascending or descending. We piloted a computer-based number ordering task with children from this age group using triads (i.e., comparable to our daily events ordering task) and found that they struggled to perform the task, even after a short training that was provided using cards representing the numbers. By contrast, they were able to complete the computer-based version of the daily events task after a training session with cards representing the events.

[2] We selected this task, rather than non-symbolic comparison, due to the inconsistency of the evidence supporting a link between non-symbolic comparison and maths in developmental studies (De Smedt, Noël, Gilmore, & Ansari, 2013), which may be, in part, due to a lack of an agreed measurement of task performance used in these studies (e.g., Inglis & Gilmore, 2014; Price, Palmer, Battista, & Ansari, 2012). In contrast, the non-symbolic addition task has been found to be a longitudinal predictor of maths achievement, as well as being related to mastery of both number words and symbols, which underlies much of early maths learning (Gilmore et al., 2010). Furthermore, other evidence (Gilmore, Attridge, De Smedt, & Inglis, 2014; Iuculano, Tang, Hall, & Butterworth, 2008) has shown that performance on non-symbolic addition and comparison tasks is correlated, suggesting that both tasks are measuring the same underlying construct, whereas non-symbolic comparison performance has been found to be unrelated to symbolic comparison performance (e.g., Sasanguie, Defever, Maertens, & Reynvoet, 2014).

[3] Although in our main analyses we considered different types of formal maths skills together, the standardized tests that we used included several different types of problems (see Methods section). We present zero-order correlations between the measures that were robustly related to maths at each time point and the different components of the formal maths tasks (see Supplementary Tables 1 and 2). Typically, the best predictors of maths at each time point (in particular, the counting task and the daily events task) were significantly related to all aspects of maths. Interestingly, symbolic number ordering was also related to all aspects of maths at T1 and T2, although it was not included in the final regression models (see below), which suggests that its effect on maths was mediated by other tasks.

[4] Additional regression analyses were performed to investigate whether the results of the cross-sectional and longitudinal regression models were the same for predicting only the arithmetic/calculation measures at T1 and T2. We conducted these analyses to demonstrate that ordering abilities were not simply related to a composite measure of maths achievement (which included various basic components of early maths ability, including some that were closely related to ordering). The same three predictors (OPQ, daily events and counting) that significantly predicted maths achievement at T1 also predicted arithmetic scores at T1 (these three predictors accounted for 31% of the variance in arithmetic scores). Three of the four significant longitudinal predictors of maths at T2 (OPQ, non-symbolic addition and daily events) also significantly predicted calculation scores at T2 (accounting for 19% of the variance in calculation scores). Age was not found to be a significant longitudinal predictor of calculation abilities. (Detailed results of these analyses can be found in Supplementary Tables 3 and 4.)

[5] The sample in Vogel et al. (2015) consisted of children in 1st grade in Canada, who were aged between 6 and 7 years old. The authors failed to find a relationship between the size of the numerical distance effect or mean reaction times for the order judgement task and maths. In Attout et al. (2014), the children were between 5 and 6 at T1; 6 and 7 at T2 and 7 and 8 at T3. There were significant associations between numerical ordering and maths at T2 and T3, but not at T1. Lyons et al. (2014) found that number ordering ability was not a significant predictor of math in grades 1 and 2 (between 6 and 8 years old) but was a significant predictor of maths from grade 3 onwards (from age 9).

ORCID

Patrick A. O'Connor http://orcid.org/0000-0003-0936-0478

REFERENCES

Aagten-Murphy, D., Attucci, C., Daniel, N., Klaric, E., Burr, D., & Pellicano, E. (2015). Numerical estimation in children with autism. *Autism Research*, *8*, 668–681.

Attout, L., & Majerus, S. (2015). Working memory deficits in developmental dyscalculia: The importance of serial order. *Child Neuropsychology*, *21*, 432–450.

Attout, L., Noël, M.P., & Majerus, S. (2014). The relationship between working memory for serial order and numerical development: A longitudinal study. *Developmental Psychology*, *50*, 1667–1679.

Berteletti, I., Lucangeli, D., Piazza, M., Dehaene, S., & Zorzi, M. (2010). Numerical estimation in preschoolers. *Developmental Psychology*, *46*, 545–551.

Berteletti, I., Lucangeli, D., & Zorzi, M. (2012). Representation of numerical and non-numerical order in children. *Cognition*, *124*, 304–313.

Bonato, M., Zorzi, M., & Umiltà, C. (2012). When time is space: Evidence for a mental time line. *Neuroscience and Biobehavioral Reviews*, *36*, 2257–2273.

Booth, J.L., & Siegler, R.S. (2006). Developmental and individual differences in pure numerical estimation. *Developmental Psychology*, *42*, 189–201.

Booth, J.L., & Siegler, R.S. (2008). Numerical magnitude representations influence arithmetic learning. *Child Development*, *79*, 1016–1031.

Butterworth, B. (2005). Developmental dyscalculia. In J.D. Campbell (Ed.), *The handbook of mathematical cognition* (pp. 455–469). New York: Psychology Press.

Chen, Q., & Li, J. (2014). Association between individual differences in non-symbolic number acuity and math performance: A meta-analysis. *Acta Psychologica*, *148*, 163–172.

Cohen, D.J., & Blanc-Goldhammer, D. (2011). Numerical bias in bounded and unbounded number line tasks. *Psychonomic Bulletin and Review*, *18*, 331–338.

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 626–641.

De Smedt, B., Noël, M.P., Gilmore, C., & Ansari, D. (2013). How do symbolic and non-symbolic numerical magnitude processing skills relate to individual differences in children's mathematical skills? A review of evidence from brain and behavior. *Trends in Neuroscience and Education*, *2*, 48–55.

Eurydice at NFER – National Foundation for Educational Research (2012). Compulsory age of starting school in European countries. Retrieved from: https://www.nfer.ac.uk/nfer/eurydice/publications/compulsory-age-of-starting-school.cfm

Fivush, R., & Hammond, N. (1990). Autobiographical memory across the preschool years: Toward reconceptualising childhood amnesia. In R. Fivush & J. Hudson (Eds.), *Knowing and remembering in young children* (pp. 223–248). New York: Cambridge University Press.

Friedman, W.J. (1977). The development of children's knowledge of cyclic aspects of time. *Child Development*, *48*, 1593–1599.

Friedman, W.J. (1990). Children's representations of the pattern of daily activities. *Child Development*, *61*, 1399–1412.

Friedman, W.J., & Brudos, S.L. (1988). On routes and routines: The early development of spatial and temporal representations. *Cognitive Development*, *3*, 167–182.

Gelman, R., & Gallistel, C. (1978). *Young children's understanding of numbers*. Cambridge, MA: Harvard University Press.

Gilmore, C., Attridge, N., Clayton, S., Cragg, L., Johnson, S., Marlow, N., … Inglis, M. (2013). Individual differences in inhibitory control, not non-verbal number acuity, correlate with mathematics achievement. *PLoS ONE*, *8*, e67374.

Gilmore, C., Attridge, N., De Smedt, B., & Inglis, M. (2014). Measuring the approximate number system in children: Exploring the relationships among different tasks. *Learning and Individual Differences*, *29*, 50–58.

Gilmore, C.K., McCarthy, S.E., & Spelke, E.S. (2010). Non-symbolic arithmetic abilities and mathematics achievement in the first year of formal schooling. *Cognition*, *115*, 394–406.

Ginsburg, H.P., & Baroody, A.J. (2003). *Test of early mathematics ability* (3rd edn.). Austin, TX: Pro-Ed.

Goffin, C., & Ansari, D. (2016). Beyond magnitude: Judging ordinality of symbolic number is unrelated to magnitude comparison and independently relates to individual differences in arithmetic. *Cognition*, *150*, 68–76.

Halberda, J., Mazzocco, M.M., & Feigenson, L. (2008). Individual differences in nonverbal number acuity predict maths achievement. *Nature*, *455*, 665–668.

Hannula, M.M., & Lehtinen, E. (2005). Spontaneous focusing on numerosity and mathematical skills of young children. *Learning and Instruction*, *15*, 237–256.

Holloway, I.D., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: The distance effect and children's mathematical competence. *Journal of Experimental Child Psychology*, *103*, 17–29.

Inglis, M., & Gilmore, C. (2014). Indexing the approximate number system. *Acta Psychologica*, *145*, 147–155.

Iuculano, T., Tang, J., Hall, C.W., & Butterworth, B. (2008). Core information processing deficits in developmental dyscalculia and low numeracy. *Developmental Science*, *11*, 669–680.

Kaufmann, L., Vogel, S.E., Starke, M., Kremser, C., & Schocke, M. (2009). Numerical and non-numerical ordinality processing in children with and without developmental dyscalculia: Evidence from fMRI. *Cognitive Development*, *24*, 486–494.

Laski, E.V., & Siegler, R.S. (2007). Is 27 a big number? Correlational and causal connections among numerical categorization, number line estimation, and numerical magnitude comparison. *Child Development*, *78*, 1723–1743.

Link, T., Huber, S., Nuerk, H.C., & Moeller, K. (2014). Unbounding the mental number line: New evidence on children's spatial representation of numbers. *Frontiers in Psychology*, *4*, 1021.

Lyons, I.M., & Beilock, S.L. (2011). Numerical ordering ability mediates the relation between number-sense and arithmetic competence. *Cognition*, *121*, 256–261.

Lyons, I.M., Price, G.R., Vaessen, A., Blomert, L., & Ansari, D. (2014). Numerical predictors of arithmetic success in grades 1–6. *Developmental Science*, *17*, 714–726.

Lyons, I.M., Vogel, S.E., & Ansari, D. (2016). On the ordinality of numbers: A review of neural and behavioral studies. *Progress in Brain Research*, *227*, 187–221.

Majerus, S., Poncelet, M., Greffe, C., & Van der Linden, M. (2006). Relations between vocabulary development and verbal short-term memory: The relative importance of short-term memory for serial order and item information. *Journal of Experimental Child Psychology*, *93*, 95–119.

Morsanyi, K., Devine, A., Nobes, A., & Szűcs, D. (2013). The link between logic, mathematics and imagination: Evidence from children with developmental dyscalculia and mathematically gifted children. *Developmental Science*, *16*, 542–553.

Morsanyi, K., O'Mahony, E., & McCormack, T. (2017). Number comparison and number ordering as predictors of arithmetic performance in adults: Exploring the link between the two skills, and investigating the question of domain-specificity. *Quarterly Journal of Experimental Psychology*, *70*, 2497–2517.

Mundy, E., & Gilmore, C.K. (2009). Children's mapping between symbolic and nonsymbolic representations of number. *Journal of Experimental Child Psychology*, *103*, 490–502.

National Center for Learning Disabilities (2007). *Understanding dyscalculia*. Retrieved from: http://www.ldonline.org/article/13709/

Nelson, K. (1986). *Event knowledge: Structure and function in development*. Hillsdale, NJ: Erlbaum.

Nelson, K. (1998). *Language in cognitive development: The emergence of the mediated mind*. Cambridge: Cambridge University Press.

Nieder, A., & Dehaene, S. (2009). Representation of number in the brain. *Annual Review of Neuroscience*, *32*, 185–208.

Northern Ireland Statistics and Research Agency (2010). Northern Ireland multiple deprivation measure 2010: Blueprint document. February 2010. Retrieved from: http://www.nisra.gov.uk/deprivation/archive/Updateof2005Measures/NIMDM_2010_Blueprint_Document.pdf

Passolunghi, M.C., Cargnelutti, E., & Pastore, M. (2014). The contribution of general cognitive abilities and approximate number system to early mathematics. *British Journal of Educational Psychology*, *84*, 631–649.

Passolunghi, M.C., & Siegel, L.S. (2001). Short-term memory, working memory, and inhibitory control in children with difficulties in arithmetic problem solving. *Journal of Experimental Child Psychology*, *80*, 44–57.

Passolunghi, M.C., Vercelloni, B., & Schadee, H. (2007). The precursors of mathematics learning: Working memory, phonological ability and numerical competence. *Cognitive Development*, *22*, 165–184.

Perez, T.M., Majerus, S., & Poncelet, M. (2012). The contribution of short-term memory for serial order to early reading acquisition: Evidence from a longitudinal study. *Journal of Experimental Child Psychology*, *111*, 708–723.

Perez, T.M., Majerus, S., & Poncelet, M. (2013). Impaired short-term memory for order in adults with dyslexia. *Research in Developmental Disabilities*, *34*, 2211–2223.

Piazza, M., Facoetti, A., Trussardi, A.N., Berteletti, I., Conte, S., Lucangeli, D., … Zorzi, M.(2010). Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. *Cognition*, *116*, 33–41.

Price, G.R., Palmer, D., Battista, C., & Ansari, D. (2012). Nonsymbolic numerical magnitude comparison: Reliability and validity of different task variants and outcome measures, and their relationship to arithmetic achievement in adults. *Acta Psychologica*, *140*, 50–57.

Rousselle, L., & Noël, M.P. (2007). Basic numerical skills in children with mathematics learning disabilities: A comparison of symbolic vs. non-symbolic number magnitude processing. *Cognition*, *102*, 361–395.

Rubinsten, O., & Sury, D. (2011). Processing ordinality and quantity: The case of developmental dyscalculia. *PLoS ONE*, *6*, e24079.

Sasanguie, D., Defever, E., Maertens, B., & Reynvoet, B. (2014). The approximate number system is not predictive for symbolic number processing in kindergarteners. *Quarterly Journal of Experimental Psychology*, *67*, 271–280.

Sasanguie, D., De Smedt, B., & Reynvoet, B. (2017). Evidence for distinct magnitude systems for symbolic and non-symbolic number. *Psychological Research*, *81*, 231–242.

Sattler, J.M., & Dumont, R. (2004). *Assessment of children: WISC-IV and WPPSI-III supplement*. San Diego, CA: Jerome M. Sattler, Publisher.

Schneider, M., Beeres, K., Coban, L., Merz, S., Schmidt, S., Stricker, J., & De Smedt, B. (2017). Associations of non-symbolic and symbolic numerical magnitude processing with mathematical competence: A meta-analysis. *Developmental Science*, *20*, e12372.

Siegler, R.S., & Booth, J.L. (2004). Development of numerical estimation in young children. *Child Development*, *75*, 428–444.

Siegler, R.S., & Opfer, J.E. (2003). The development of numerical estimation: Evidence for multiple representations of numerical quantity. *Psychological Science*, *14*, 237–250.

Soltész, F., Szűcs, D., & Szűcs, L. (2010). Relationships between magnitude representation, counting and memory in 4- to 7-year-old children: A developmental study. *Behavioral and Brain Functions*, *6*, 1–14.

Szűcs, D., Devine, A., Soltesz, F., Nobes, A., & Gabriel, F. (2013). Developmental dyscalculia is related to visuo-spatial memory and inhibition impairment. *Cortex*, *49*, 2674–2688.

Tillman, K., Tulagan, N., & Barner, D. (2015). Building the mental timeline: Spatial representations of time in preschoolers. *Proceedings of the Cognitive Science Society*.

Van Der Ven, S.H., Van Der Maas, H.L., Straatemeier, M., & Jansen, B.R. (2013). Visuospatial working memory and mathematical ability at different ages throughout primary school. *Learning and Individual Differences*, *27*, 182–192.

van Dijck, J.P., Abrahamse, E.L., Majerus, S., & Fias, W. (2013). Spatial attention interacts with serial-order retrieval from verbal working memory. *Psychological Science*, *24*, 1854–1859.

van Dijck, J.P., & Fias, W. (2011). A working memory account for spatial–numerical associations. *Cognition*, *119*, 114–119.

Van Heuven, W.J., Mandera, P., Keuleers, E., & Brysbaert, M. (2014). SUBTLEX-UK: A new and improved word frequency database for British English. *Quarterly Journal of Experimental Psychology*, *67*, 1176–1190.

Vogel, S.E., Remark, A., & Ansari, D. (2015). Differential processing of symbolic numerical magnitude and order in first-grade children. *Journal of Experimental Child Psychology*, *129*, 26–39.

von Aster, M.G., & Shalev, R.S. (2007). Number development and developmental dyscalculia. *Developmental Medicine and Child Neurology*, *49*, 868–873.

Vos, H., Sasanguie, D., Gevers, W., & Reynvoet, B. (2017). The role of general and number-specific order processing in adults' arithmetic performance. *Journal of Cognitive Psychology*, *29*, 469–482.

Wechsler, D. (2003). *Wechsler Preschool and Primary Scale of Intelligence – Third UK Edition (WPPSI-III)*. Oxford: Psychological Corp.

Williams, J. (2005). *Mathematics assessment for learning and teaching*. London: Hodder Education.

Woodcock, R.W., McGrew, K.S., & Mather, N. (2001). *Woodcock-Johnson tests of achievement*. Itasca, IL: Riverside Publishing.

SUPPORTING INFORMATION

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APPENDIX

Parental Order-Processing Questionnaire

Please circle the number which you feel best applies to your child for each question

(1 = very much disagree; 7 = very much agree)
My son/daughter:

Is easily confused by changes in routine	1----2----3----4----5----6----7
Understands how the seasons of the year follow each other (e.g., that autumn always comes after summer)	1----2----3----4----5----6----7
Can easily recall the order in which past events happened	1----2----3----4----5----6----7
Is able to plan a sequence of activities independently	1----2----3----4----5----6----7
Finds it difficult to learn new activities which involve a sequence of actions which have to be performed in a particular order (e.g., putting together the parts of a toy in the right order)	1----2----3----4----5----6----7
Would be able to recall the order of typical daily events	1----2----3----4----5----6----7
Understands that some things always have to be done in a particular order (e.g., putting on a school shirt before putting on a tie)	1----2----3----4----5----6----7
Finds it difficult to understand how the days of the week follow each other (e.g., knowing that Wednesday comes after Tuesday)	1----2----3----4----5----6----7

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Developmental Dyscalculia is Characterized by Order Processing Deficits: Evidence from Numerical and Non-Numerical Ordering Tasks

Kinga Morsanyi[a], Bianca M.C.W. van Bers[a,b], Patrick A. O'Connor[a], and Teresa McCormack[a]

[a]School of Psychology, Queen's University Belfast, Belfast, Northern Ireland; [b]Department of Psychology, University of Amsterdam, Amsterdam, Netherlands

ABSTRACT
This study tested the hypothesis that individuals with dyscalculia have an order processing deficit. The ordering measures included both numerical and non-numerical ordering tasks, and ordering of both familiar and novel sequences was assessed. Magnitude processing/estimation tasks and measures of inhibition skills were also administered. The participants were 20 children with developmental dyscalculia, and 20 children without maths difficulties. The two groups were closely matched on age, gender, socio-economic status, educational experiences, IQ and reading ability. The findings revealed differences between the groups in both ordering and magnitude processing skills. Nevertheless, diagnostic status was best predicted by order processing abilities.

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Developmental dyscalculia (DD) is a specific impairment of mathematical ability, which may affect 3.5–6.5% of the population (e.g., Butterworth, 2005; Kaufmann & von Aster, 2012; Morsanyi, van Bers, McCormack, & McGourty, 2018; von Aster & Shalev, 2007). Individuals with DD are characterized by moderate to extreme difficulties in fluent numerical computations in the absence of sensory difficulties, low IQ, or educational deprivation (Butterworth, 2005). Different theories regarding the causes of DD have been proposed. A cognitive neuroscience theory that has dominated research into DD for several years assumes that the specific difficulties in mathematics originate in the impairment of a specialized magnitude representation system, the approximate number system (ANS; Piazza et al., 2010) or 'number module' (Landerl, Bevan, & Butterworth, 2004). Others have suggested that DD results from impaired connections between these magnitude representations and numerical symbols (De Smedt & Gilmore, 2011; Iuculano, Tang, Hall, & Butterworth, 2008; Rousselle & Noël, 2007).

Besides theories of DD that are related to magnitude representation, behavioral research has proposed other theories that focus on the role of more general cognitive resources in mathematics. For example, there is evidence that deficits in verbal and visual working memory (Bull & Scerif, 2001; Geary, 2004, 2011; Hitch & McAuley, 1991; Mammarella, Hill, Devine, Caviola, & Szűcs, 2015; Passolunghi & Siegel, 2001, 2004; Szűcs, Devine, Soltész, Nobes, & Gabriel, 2013; Swanson, 2011), inhibitory function (Blair & Razza, 2007; Bull & Scerif, 2001; Espy et al., 2004; Szucs, Devine et al. 2013; Swanson, 2011) and attentional function (Ashkenazi, Rubinsten, & Henik, 2009; Hannula, Lepola, & Lehtinen, 2010; Szucs, Devine et al., 2013; Swanson, 2011) may be linked to DD.

CONTACT Kinga Morsanyi k.morsanyi@qub.ac.uk School of Psychology, Queen's University Belfast, Belfast, BT7 1NN, Northern Ireland, UK

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More recently, the relation between order processing and mathematics ability has attracted much attention. According to Rubinsten and Sury (2011), numerical cognition might depend on two core systems, one for representing magnitudes (i.e., cardinality) and one for representing ordinal information. These authors have proposed that it might be the system responsible for order processing (rather than the magnitude system) that is impaired in DD. Indeed, in recent years, an increasing number of studies have investigated the role of order processing in maths, demonstrating its role in both typical mathematical development (e.g., Attout, Noël, & Majerus, 2015; Lyons & Ansari, 2015; Lyons, Price, Vaessen, Blomert, & Ansari, 2014; Lyons, Vogel, & Ansari, 2016; O'Connor, Morsanyi, & McCormack, 2018; Vogel, Remark, & Ansari, 2015) and in mature mathematics skills (e.g., Goffin & Ansari, 2016; Lyons & Beilock, 2011). Most of these studies have focussed on number ordering ability, which is typically measured using a task where three one-digit numbers are presented (e.g., 6 4 7), and participants have to decide if these number are in the correct order with regard to their position in the count list. Some studies with adults (Morsanyi, McCormack, & O'Mahony, 2018; Morsanyi, O'Mahony, & McCormack, 2017; Sasanguie, Lyons, De Smedt, & Reynvoet, 2017; Vos, Sasanguie, Gevers, & Reynvoet, 2017) not only showed a close link between number ordering and arithmetic skills, but they also found strong relations between non-numerical ordering abilities and maths. One particular task that has been used in this literature is the month ordering task, where participants have to judge if three months (e.g., May June August) are presented in the correct order with regard to their order within a calendar year. In addition to these lab-based studies, clinical observations of dyscalculia also describe characteristic difficulties with everyday activities that require ordering skills (e.g., recalling the order of past events, following sequential instructions, etc., National Center for Learning Disabilities, 2007).

Nevertheless, apart from the study of Rubinsten and Sury (2011), so far only a handful of studies have investigated the role of order processing abilities in DD (Attout & Majerus, 2014; Attout, Salmon, & Majerus, 2015; De Visscher, Szmalec, Van der Linden, & Noel, 2015; Kaufmann, Vogel, Starke, Kremser & Schocke, 2011). These studies provide initial evidence that not only numerical, but also non-numerical ordering skills are impaired in dyscalculia (though see Kaufmann et al., 2011). In particular, previous studies suggest an impairment in learning and remembering serial order information. For example, De Visscher et al. (2015) investigated serial learning ability in dyscalculia, using the Hebb learning paradigm, where participants were repeatedly presented with lists consisting of nine syllables until they learnt to recall the sequences in the correct order. They found that participants with dyscalculia showed a reduced ability to learn and retain the sequences. Given that the sequences used in this study included non-numerical items, these results suggest that dyscalculic participants show a general deficit in serial order learning (which is likely to also affect the learning of numerical sequences, although this was not investigated in the study). However, as discussed below, we do not yet know the full nature and extent of order processing problems in dyscalculia. In particular, much is not yet known about deficits in processing non-numerical information. Attout's studies (Attout & Majerus, 2014; Attout, Salmon & Majerus., 2015) and that of De Visscher et al. (2015) examine only the ability to learn and remember short novel sequences of non-numerical items, whereas the numerical system itself is a highly familiar one that requires flexible use of ordinal information. It is not yet clear whether deficits in order processing in DD extend to other familiar ordered sequences, whether different aspects of order processing are differentially impaired in DD, and the status of impairments in order processing relative to other types of impairments observed in this population. These issues are addressed in the current study.

The current study

Given that order processing in dyscalculia is a relatively neglected issue, the main aim of the study was to conduct a systematic investigation into ordering skills in children with DD. We tested ordering abilities both in the domain of numbers and in non-numerical domains, such as the domain of time, and everyday activities with an ordering component. Another question that we wanted to address was whether the ordering deficits (if present) affect ordering skills related to familiar sequences (e.g., numbers, familiar everyday events and activities, and the events of the calendar year), as well as short novel sequences (e.g., lists of unrelated words or spatial locations). This way we could assess both the extent and the nature of the order processing deficits in DD.

Although it might be thought that ordering of familiar and unfamiliar sequences rely on similar processes, there are good reasons to assume that these are distinct skills. Tasks that assess memory for short unfamiliar sequences of items assess a key aspect of short-term or working memory (and are subject to effects related to the limited capacity of working memory resources), whereas tasks that involve making judgments about the order of familiar sequences (either numerical or non-numerical) rely on retrieving and using ordinal information stored in long-term memory (cf., Attout, Noel & Majerus., 2015). Although it can be expected that the two skills are related (e.g., it is necessary to temporarily retain sequences in working memory in order to transfer them into long-term memory storage), it is possible that a person who struggles with the temporary storage of arbitrary sequences, after sufficient practice, is able to store these sequences in long-term memory and make use of them efficiently. Consistent with the idea that tasks assessing order WM and tasks that require long-term memory for familiar sequences tap at least partially independent skills, O'Connor et al. (2018) found that the two tasks showed only a moderate relationship, and that performance on the latter type of task was predictive of maths skills over and above the former. In this study, we looked at both types of abilities.

Regarding the choice of ordering tasks, the two most relevant previous studies for our purposes were the studies by Attout and Majerus (2014) and Kaufmann et al. (2011). Both studies used a number ordering task, which required that participants judge the correctness of the order of three numerals. Whereas Kaufmann et al. (2011) only found differences between dyscalculic and non-dyscalculic children in their brain activation patterns, Attout and Majerus (2014) reported a difference in reaction times, with longer RTs in the DD group. Additionally, Attout and Majerus (2014) also used an order working memory task (the animal race task), which involved recalling lists of animal names in the correct order in a task that placed minimal demands on item memory. Attout and Majerus (2014) found impaired order memory in children with DD. Subsequently, they replicated this finding with adults with a history of dyscalculia (Attout et al., 2015). In order to investigate order processing skills in DD further, in the current study, we used both the order memory and the number ordering tasks. Given reports that spatial working memory is impaired in dyscalculia (e.g., Mammarella et al., 2015; Szucs, Devine et al., 2013), and because the order memory task only included verbal materials, we also administered a visual-spatial working memory task that also required order recall.

The novelty of our study was the addition of two further measures of non-numerical order processing. Although Attout and Majerus (2014) assessed non-numerical order processing, their non-numerical task only assessed the ability to hold ordered sequences temporarily in working memory. Their numerical ordering task (judging whether three numbers are in the correct order), performance on which was also impaired in DD, draws on long-term memory representations of a familiar sequence. What is not known is whether the impairments in DD extend to tasks involving long-term memory representations of non-numerical order. Such impairments would indicate that DD is characterized by more generalized difficulties in representing and using order information. Such generalized difficulties would be consistent with recent findings that non-numerical order processing is strongly related to maths skills in typical adults (Morsanyi et al., 2017; Vos et al., 2017).

Indeed, clinical reports of dyscalculia describe difficulties with everyday activities with an ordering requirement. The link between mathematics skills and everyday ordering abilities was supported by a recent study (O'Connor et al., 2018), which was conducted with young children at the start of their formal education. Parents were asked to complete a short questionnaire that included items, such as: "My son/daughter would be able to recall the order of typical daily events". The parents' ratings of their children's everyday ordering abilities strongly predicted their formal mathematics skills at the end of their first, as well as their second school year, even after controlling for the effect of the socio-economic status and IQ of the children. In the current study, we used this questionnaire with some modifications to make the questions age-appropriate.

The same study by O'Connor et al. (2018) found that young children's performance on a non-numerical ordering task at the start of the first school year also strongly predicted their formal maths skills at the end of the first and second year of school. The task that they used was designed to be similar to the number ordering task. However, instead of a triad of numbers, pictures of three familiar daily events were presented (e.g., having breakfast, going to bed at night, going to school), and children were asked to judge whether the order was correct or incorrect. A strong link between ordering in the time domain (i.e., ordering of the months of the calendar year) and maths skills was also reported by recent studies with adults (e.g., Morsanyi et al., 2018; Vos et al., 2017).[1] For this reason, we also administered a task which required the correct ordering of familiar events in time. O'Connor et al. (2018) used pictures of familiar daily events, and the adult studies used written month names. In the current study, we relied on pictorial presentations, so that reading ability did not affect ordering performance. However, instead of pictures of daily events, we presented the children, who were aged 9–10 years, with pictures of familiar events of the calendar year. Whereas even 4-year-olds can make correct judgments about the order of typical daily events, children gradually develop representations of the relative order of recurring events of the calendar year during middle-childhood (Friedman, 1990, 2000, 2002). For this reason, we considered the annual event ordering task as more age-appropriate than a daily event ordering task.

Magnitude processing and estimation

In addition to ordering skills, we investigated magnitude processing/estimation skills that are traditionally considered to be impaired in dyscalculia. We thought that it was important to investigate these abilities side by side, in order to see which tasks discriminate the best between dyscalculic and non-dyscalculic children, and also to see if ordering and magnitude processing skills are related. On the basis of past research, three tasks seemed particularly relevant: the number comparison task (which measures symbolic comparison skills), the dot comparison task (which measures non-symbolic magnitude comparison abilities), and the number line task (which measures the ability to translate between symbolic and non-symbolic representations of magnitudes, and is also assumed to include an ordering component).

Although there is evidence to suggest that children with DD show impairments on both the number comparison task and the dot comparison task, some researchers have argued that non-symbolic magnitude processing might be intact in DD, whereas the processing of symbolic magnitudes is impaired (De Smedt & Gilmore, 2011; Iuculano et al., 2008; Rousselle & Noël, 2007). Indeed, both the behavioral and neuroscientific evidence regarding differences on the dot comparison task between DD and non-DD participants is inconsistent (see Szucs, Devine et al., 2013 for a review and discussion), meaning further investigation is valuable. There are various versions of the dot comparison task, which differ both in the number of stimuli presented (i.e., whether they also include numbers in the subitizing range), and the perceptual properties of the displays. Previous studies that reported differences in dot comparison performance between DD and control participants (e.g., Mazzocco, Feigenson, & Halberda, 2011; Mussolin, Mejias, & Noël, 2010; Piazza et al., 2010; Price, Holloway, Räsänen, Vesterinen, & Ansari, 2007; Skagerlund & Träff, 2016) also used various designs. We decided to model our task on Price et al. (2007), because their study showed both behavioral and fMRI evidence for group differences in the version of the dot comparison task that they used. The number of items in their task ranged between 1 and 9 (i.e., they also included numbers in the subitizing range).

A final task related to estimation/magnitude processing skills that we used was the number line task, which is a strong predictor of mathematics skills in the first school years (e.g., Booth & Siegler, 2006, 2008; De Smedt, Verschaffel, & Ghesquière, 2009; Lyons et al., 2014). Additionally, von Aster and Shalev (2007) proposed that the core deficit characterizing DD was an impaired ability to represent and manipulate numerical magnitudes nonverbally on an internal number line. In line with this claim, Skagerlund and Traff (2016) found greater estimation errors in a number line task in dyscalculic than in typically developed children. This task is also very relevant for our study, because it is considered to combine the need for estimation skills with an understanding of ordinality (cf., Kaufmann & von Aster, 2012; von Aster & Shalev, 2007).

Inhibition

Inhibition skills are important for mathematics (e.g., Blair & Razza, 2007; Bull & Scerif, 2001), and Szucs, Devine et al.,(2013) proposed that impairments in inhibition might be a defining feature of DD. We investigated response inhibition using the stop signal task, given that Szucs, Devine et al., (2013) reported a difference between DD and non-DD children in stop signal accuracy (indeed, this was the only inhibition task where they reported accuracy differences). In addition, we measured sensitivity to interference by examining the effect of perceptual congruency in the dot comparison task. Gilmore et al. (2013) and Szucs, Devine et al., (2013) highlighted the Stroop-like properties of the dot comparison task (i.e., that the congruency between numerosity and the perceptual properties of the stimuli are systematically manipulated), and Gilmore et al. (2013) argued that this property of the task might explain the link between dot comparison performance and mathematics skills. Additionally, Szucs, Devine et al., (2013) found a greater effect of perceptual congruency in the dot comparison task in DD than in a control group (although see Rousselle & Noël, 2007). Together, the stop signal task and this measure from the dot comparison task examined two partially independent aspects of inhibitory control (see Friedman & Miyake, 2004): response control and suppression of interference.[2]

Summary

In summary, this study investigated the core impairments underlying DD. We were particularly interested in whether ordering skills were impaired in DD, and, if this was the case, in the extent and nature of these deficits. In addition to conducting the most comprehensive investigation into order processing skills in DD so far, we also investigated the evidence regarding magnitude processing and inhibition deficits, to get a full picture of the range of difficulties that characterize DD. Within the tasks that we employed, we systematically manipulated some factors (e.g., perceptual congruency, numerical/magnitude differences, etc.) with the aim of comparing the effects of these manipulations between groups. This way we could investigate the cognitive processes that underlie performance on these tasks in children with and without DD. Finally, we selected the children in the DD group very carefully to make sure that all of these children had persistent and specific difficulties in mathematics, and we used rigorous methods to match the DD and control groups.

Method

Selection of participants

The children in this study were allocated to a DD group or a control group after a two-step screening procedure. First, 19 schools had been contacted and permission was sought to access the schools' records of children's (n = 3,345) performance on age-standardized national curriculum-based mathematics, English and IQ tests. The schools administer standardized tests of mathematics and English every year, starting from year 3. The schools also administer standardized IQ tests, although the timing and frequency of testing varies between schools. Typically, the schools administer IQ tests twice during the primary school years. The standardized achievement tests used by the schools were the *Progress in Maths* (PiM) test, and the *Progress in English* (PiE) test. Additionally, the schools used either (or both) of the following standardized IQ tests: The *Cognitive Abilities Test-Fourth Edition* (CAT4) or the *Non-Reading Intelligence Test* (NRIT).

One hundred-and-twenty children from the original sample, who attended years 5, 6, or 7 of seven different primary schools, were invited to participate in a screening session. The seven schools were selected on the basis that they had a relatively high number of children with a potential diagnosis of DD. Forty children were invited for potential inclusion in the DD group, and 80 children were selected for potential inclusion in the control group. The children were considered for inclusion in the DD group if their standardized score on the PiM was at least 1 *SD* below the population mean (i.e., they had a score of 85 or lower) for at least two academic years (indicating persistent difficulties with maths), whereas their PiE score and their IQ score were close to the population mean (i.e., at least 86 for all school years, although children with higher scores were preferred). Children were considered for potential inclusion in the control group if they attended the same schools and classes as the children in the potential DD group, and they were similar in age, gender, and their recent PiE and CAT/NRIT scores. The PiM score of the children in the potential control group was close to the population mean (see more on this below). Children with an official diagnosis of a developmental disorder (other than mathematics difficulties in the case of the DD group) were excluded from the study.

In the second step of the selection procedure, the 120 children who were pre-selected in the first step were administered an additional standardized measure of mathematics ability, a standardized measure of reading ability, and an IQ test by the researchers (see Materials section). Children from the potential DD group were included in the final DD sample if this additional testing confirmed that they had a standardized score on the maths test that was at least 1 *SD* below the population mean (i.e., a score of 85 or lower), and they had a discrepancy between their IQ and mathematics score of at least 7 standardized points (i.e., a magnitude of 0.5 *SD* relative to population standards) or a discrepancy of at least 7 points between their standardized mathematics and reading scores, as measured by the researchers.[3] We aimed to recruit children with a relatively large discrepancy between their mathematics and IQ/reading scores (see Table 1), in order to make sure that children in the DD group had specific difficulties in mathematics. Children from the potential control group were excluded from the final sample if they had standardized mathematics scores under 90 from any academic year (based either on the scores collected by the schools or the researchers). We did this to make sure that none of the children in the control group had any hint of mathematics difficulties.

Participants

On the basis of the selection criteria, 20 children (7 girls) were included in the final DD group. Twenty additional children (10 girls) were included in the control group, who were matched to the children in the DD group as closely as possible on age, gender, IQ and standardized reading scores. In particular, we aimed to minimize group differences in IQ while also matching the groups closely on the other relevant factors. Additionally, control children were selected from the same schools and classes as the children with DD. The characteristics of the two groups are presented in Table 1. There was one child in the DD group, and two children in the control group who did not speak English as

Table 1. Characteristics of the children in the DD and control groups.

	DD (n = 20) Mean (*SD*)	Control (n = 20) Mean (*SD*)	*p*
Age	113.75 *(8.66)*	117.70 *(8.11)*	.145
Gender (1 = *male*; 0 = *female*)	0.65 *(0.49)*	0.50 *(0.51)*	.350
Free school meals (1 = *yes*; 0 = *no*)	0.75 *(0.44)*	0.75 *(0.44)*	1.00
Standardized mathematics score	79.45 *(5.48)*	97.65 *(6.89)*	< .001
Standardized reading score	86.70 *(10.19)*	89.70 *(5.91)*	.262
IQ	87.05 *(9.25)*	86.85 *(7.32)*	.940

their first language. Nevertheless, the researchers judged that these children had appropriate English language skills to be able to participate in the study. Regarding the socio-economic status of the children, there were 15 children in each group who were eligible for free school meals. The most common reason for children to be eligible for free school meals is that their parent/guardian experiences economic hardship. Thus, on average, children in the sample had a relatively low socio-economic status. The primary schools that the children were recruited from represented a mix of urban schools and outlying rural schools. The study received approval from the School of Psychology research ethics committee at the authors' university. Informed consent was obtained from the schools and the parents of all children who participated. Additionally, verbal assent was obtained from each child at the start of each testing session.

Materials

Standardized mathematics test: the *Mathematics Assessment for Learning and Teaching* test (MaLT; Williams, 2005) is a group-administered written test. The MaLT test was developed in accordance with the National Curriculum and National Numeracy Strategy for England and Wales. Test items cover: counting and understanding number (12 items – these tasks included counting forward or backward in steps of constant size – e.g., 5 9 _ 17 21 25), knowing and using number facts (2 items which included deriving and recalling facts related to arithmetic operations – e.g., (5 × 7) – _ = 29), calculating (11 items – e.g., "What number is 10 less than 4,000?"), understanding shape (6 items – e.g., finding the missing piece of a jigsaw based on a picture), measurement (7 items – e.g., finding the area of polygon presented in a grid), and handling data (7 items – interpreting data presented in graphs or pictograms – e.g., using a daily temperature chart, answering the following question: "How many days was the temperature less than 11°C?"). This test allows for invigilators to read the questions to the children, if required, to ensure that test performance reflects mathematics ability rather than reading proficiency. The MaLT test was standardized in 2005 with children from 120 schools throughout England and Wales (MaLT 9, $\alpha = 0.93$; MaLT 10, $\alpha = 0.92$). Children had to complete the test within 45 minutes.

Standardized reading test: the *Hodder Group Reading Test II* (HGRT II; Vincent & Crumpler, 2007) is a group-administered multiple-choice test that assesses children's reading of words, sentences and passages. The test was standardized in 2005 with children from 111 primary and secondary schools throughout England and Wales (HGRT-II, level 2, $\alpha = 0.95$). The test has two parallel forms, which were used in the current project to minimize copying. Children had to complete the test within 30 minutes.

IQ test: a short form of the *Wechsler Intelligence Scale for Children-fourth edition* (WISC-IV UK; Wechsler, 2003) that consisted of the block design (non-verbal) and vocabulary (verbal) subtests was individually administered to each participant. This combination of subtests has the highest validity and reliability of the two-subtest short forms of the WISC, and, on the basis of these tasks, full-scale IQ scores can be estimated using the method outlined by Sattler and Dumont (2004).

Order processing tasks

A short questionnaire, the *Parental Report of Everyday Ordering Ability*, was administered to obtain parents' ratings of their child's ability to perform everyday tasks that involve order processing. The questionnaire was an adapted version of the scale used by O'Connor et al. 2018. As the original scale was developed for 4-to-5-year-olds, some items were modified to make them appropriate for older children. The parents were asked to rate on a 7-point Likert scale (ranging from *1 = totally disagree* to *7 = totally agree*) a list of seven statements referring to everyday ordering tasks, such as remembering schedules, planning sequential actions, and carrying out tasks in the appropriate order. Example questions are: "My son/daughter can easily adjust to changes in routine." or "My son/daughter is able to plan a sequence of activities independently" (see Appendix for the full questionnaire). A sum score was computed for the scale. In the present sample, Cronbach's alpha was 0.85.

The *order working memory task* (the animal race), based on the task used by Majerus, Poncelet, Greffe, and van der Linden (2006), was administered to measure working memory for order. The stimuli used for this task were seven monosyllabic animal names: cat, dog, sheep, bird, bear, horse and fish. Only names with high lexical frequency were used to minimize the requirement to remember the names. The seven animal names were used to form lists with lengths ranging from two to seven items, and there were four trials at each list length. The items were selected randomly from the pool of seven items, and no item could occur twice in the same list. The stimuli were presented by increasing list length. Each stimulus list was presented via headphones, with the experimenter activating each list presentation. After the auditory presentation of the list of animal names, the child was given cards, depicting the animals in the list. Thus, for example, for list length 2 the child received two cards depicting the animals in the list. The child then had to arrange the cards (given in alphabetical order) to match the order of presentation of the auditory sequence by putting them on a cardboard sheet with a staircase-like platform. The child was told whenever the list length increased. Testing was terminated when more than two lists of the same length were reconstructed incorrectly. A point was given to the child for each list that was correctly reconstructed, with every item placed in the appropriate position. These scores were summed to obtain a total correct score. Additionally, a span score was computed, based on the length of the list that the child was able to recall. To have a span score of 3, a child had to be able to recall at least two out of the four lists with three items correctly. In the present sample, the split-half reliability of the total score (using the Spearman-Brown formula to compare performance on the first two vs. the second two trials at each set length) was 0.92.

A computerized version of the backward matrices task was administered to measure visuospatial working memory (based on the task used by Mammarella et al., 2015). The task involves remembering the location and the order of blue squares displayed sequentially in a 4 × 4 grid on a computer screen. The children were asked to recall the location of the blue squares in *reverse order*. The number of squares in the sequence was successively increased from two to eight. Two practice trials were presented, followed by 14 experimental trials (two trials at each sequence length). Children worked through all trials regardless of their performance. A point was given to the child for each sequence that was correctly recalled, and these scores were summed to obtain a total score. Additionally, a span score was computed, based on the number of locations that the child was able to recall in the correct order. To have a span score of 3, a child had to be able to recall at least one out of the two three-item sequences correctly (if a child failed both trials with 3 items, but was able to complete at least one 4-item trial correctly, he or she was allocated a span score of 4). Nevertheless, span scores were only used to make it easier to interpret the performance of the children at the group levels. We used total scores for our main analyses, as we considered these more reliable. In the present sample, the split-half reliability (using the Spearman-Brown formula to compare performance on the first vs. second trial at each sequence length) was 0.68.

Ordinal judgment tasks

Two computerized tasks were administered. One of these was designed to measure *number ordering ability*.[4] In this task, children were presented with number triads (e.g., 2 3 7), and they were asked to decide whether the triads were in the correct increasing order from left to right, irrespective of the numerical distance between the numbers. All numbers were between 1 and 9. Four practice trials were presented, followed by 48 experimental trials. Cronbach's alpha for our sample was 0.92 for accuracy and 0.86 for RT.

An additional task, specifically designed for the current study, was administered to measure *annual event ordering* (based on Friedman, 2002). Children were presented with three pictures referring to special days or events during the calendar year (e.g., Easter, Halloween and Christmas), and were asked to indicate whether the triads were in the correct order from left to right, the way these events happen during one calendar year. The nine events included were Valentine's day, Easter, sports day (held by the schools in June every year), summer holiday, going back to school after the summer holiday, Halloween, Christmas, New Year's Eve and the child's birthday. As in the number ordering task, four practice trials were presented, followed by 48 experimental trials. Before starting the computer-based task, children were presented with cards representing each yearly event, and they were asked to name the events, and to put them in the correct order as they happen during the calendar year. This was done to make sure that errors in the task do not arise from children not recognizing the events represented by the cards. Cronbach's alpha was 0.89 for accuracy and 0.91 for RT.

The trials in the number ordering and annual event ordering tasks were matched, so that for each number ordering trial there was a corresponding event ordering trial. The number triad 2 3 8 for example, might correspond to the event triad of Easter, sports day and Christmas because Easter is the second event happening during the year, sports day is the third event and Christmas the eighth event. (Depending on the child's birthday, different versions of the task were created to ensure the correspondence between the number and event ordering tasks.) The trials in both tasks were designed so that the distance between the two extreme numbers/events within each triad was systematically manipulated. The smallest distance was 2 (three consecutive numbers/events) and the largest distance was 7. For each distance, eight trials were presented in each task (four in the correct order and four in mixed order). Triads including the two extreme numbers and events were not included to avoid the possibility that participants respond to these trials using a response rule that does not necessitate the on-line checking of order within the triads. Additionally, to ensure that participants processed all three items within the triads, in the case of mixed order triads the first two items always appeared in the correct order.

Magnitude comparison and estimation tasks

A computerized task was administered to measure *symbolic number comparison* ability (based on the task used by Dehaene, Dupoux, & Mehler, 1990). Children were presented with two one-digit numerals between 1 and 9, one on the left side of the screen and the other one on the right side, and they were asked to indicate which number was larger. The distance between the two numbers was systematically manipulated between 1 and 6. For each distance, eight trials were presented (resulting in a total of 48 experimental trials). The task started with four practice trials. Cronbach's alphas for both accuracy and RTs were 0.96.

Another computerized task was developed to measure *non-symbolic comparison ability*. This task was modeled on Price et al. (2007) in terms of the number of stimuli in the displays and their perceptual properties. Nevertheless, we followed Gilmore, Attridge, De Smedt, and Inglis (2014) in some other respects, namely in the contextualization of the task and in the timing of the display presentation. In this task, children were presented with two arrays of blocks, one array on the left side of the screen and one on the right side, and they were asked to indicate which array contained more blocks. Each array contained between 1 and 9 blocks. The stimuli were created in such a way that continuous quantity variables, such as area and density of the squares could not be reliably used to select the correct array. Additionally, on half of the trials, the array with more blocks had a bigger total surface area (congruent trials), and in the other half the array with more blocks had a smaller total surface area (incongruent trials). The numerical difference between the two arrays was systematically manipulated between 1 and 6, and, for each difference, eight trials were presented. The task was presented as a game in which the arrays showed how many sweets each of two children had. The arrays were presented for 1 second, after which they disappeared from the computer screen. Once the blocks disappeared from the screen, the children were prompted to indicate which of the two characters had more sweets. Four practice trials were presented, followed by 48 experimental trials. In the present sample, Cronbach's alpha was 0.50, which is poor, but not unacceptable (Kline, 2000).

A computerized version of the *number line estimation task* was administered to assess children's ability to spatially represent numbers along a mental number line. This task was based on the number-to-position problems used by Siegler and Opfer (2003). In each problem, children were presented with a number and asked to estimate where it would appear on a number line by using the mouse to click on the line. We used two different scales for the task: a 0–100, and a 0–1000 scale. Both scales were 1,000 pixels long, which made the errors of estimation (i.e., the distance in pixels between the correct position of the target number and children's estimation of the position of the number) across scales directly comparable. The task included 10 problems for each scale. The numbers presented were 2, 3, 4, 6, 18, 25, 42, 67, 71 and 86 for the 0–100 scale and 4, 6, 18, 25, 71, 86, 230, 390, 780, 810 for the 0–1,000 scale. Errors were averaged across all 10 trials for each scale, with a higher number indicating worse performance. Cronbach's alpha for the estimation errors was 0.79.

Inhibition

The *stop signal task* (Logan & Cowan, 1984) was administered to measure response inhibition. In the task, a smiley face was presented on a black background in the middle of the screen. The smiley face was followed by a white arrow, which was pointing left or right. The presentation of the arrow was followed by either a sound (the stop signal) or no sound. Children were required to indicate the direction of the arrow using a key press during go trials, and to withhold their response during stop trials. A block of 30 go trials was administered first to calculate the mean RT of the child. This was followed by 140 alternating go and stop trials, which were presented in three blocks: a practice block with 28 trials, and two experimental blocks with 56 trials each. The stop signal was presented at four different intervals: 200, 300, 400 and 500 ms before the mean RT of the child, calculated on the basis of the first block of go trials. In the case of go trials, children had to respond within a 1000 ms time window. Twelve trials of each interval were administered in total in the last two blocks, leading to a ratio of go and stop trials of 2.33:1. Mean accuracy of the stop trials in blocks 3 and 4 was calculated as a measure of performance. Cronbach's alpha for our sample was 0.84.

We also administered a *choice reaction time task* (based on Fry & Hale, 1996) to measure basic processing speed, given that some of our other tasks involved RT measures. Children were asked to press a red or a blue button in response to the presence of a red or a blue circle on the computer screen. Forty trials were administered (half red, half blue). Performance was indexed by children's mean RT for correct trials. Cronbach's alpha for the present sample was 0.94.

Procedure

The participants completed the tasks in three testing sessions. The order in which the tasks were presented was the same for all participants. The first session was a group session, which took approximately 80 minutes. In this session, the participants were administered the MaLT and the HGRT-II. The other two sessions were individual sessions of about 35 minutes. In the first individual session, the children completed the following tasks (in this order): backward matrices, choice RT, annual events ordering, symbolic comparison, and order working memory. The second individual session started with the number line estimation task. This was followed by number ordering, the stop signal task, non-symbolic comparison, and the two subtests of the WISC-IV: block design and vocabulary. On average, there were 7 days between the group session and the first individual session, and two days between the first individual session and the second individual session.

Table 2. Performance on each task in the DD and control groups.

	DD (n = 20) Mean (*SD*)	Control (n = 20) Mean (*SD*)
Parental Questionnaire	35.85 *(8.26)*	41.45 *(6.27)*
Order working memory	10.75 *(3.14)*	13.60 *(3.35)*
Backward matrices	4.60 *(1.81)*	5.75 *(1.58)*
Number ordering accuracy	.82 *(.16)*	.91 *(.14)*
Number ordering RT (ms)	3372 *(1431)*	2448 *(838)*
Annual event ordering accuracy	.70 *(.17)*	.78 *(.17)*
Annual event ordering RT (ms)	3791 *(1901)*	4025 *(1674)*
Number comparison accuracy	.86 *(.20)*	.93 *(.15)*
Number comparison RT	1276 *(552)*	964 *(267)*
Dot comparison accuracy	.91 *(.06)*	.95 *(.03)*
Number line estimation error (pixels)	123 *(49)*	85 *(38)*
Stop signal task accuracy	.86 *(.09)*	.83 *(.14)*
Choice RT task accuracy	.92 *(.09)*	.96 *(.03)*
Choice RT (ms)	608 *(160)*	540 *(115)*

Table 3. Correlations between the tasks used in the study (correlations in brackets represent partial correlations after controlling for the effect of group membership).

	Parental questionnaire	Order WM	Backward matrices	Number ordering	Annual event ordering	Number comparison	Dot comparison	Number line	Stop signal
Parental questionnaire	–								
Order WM	–.005 (–.18)	–							
Backward matrices	.04 (–.09)	.37* (.27)	–						
Number ordering	.21 (.11)	.31* (.22)	.50**(.44**)	–					
Annual event ordering	.22 (.14)	.13 (.04)	.35* (.29)	.60** (.57**)	–				
Number comparison	.09 (.02)	.27 (.21)	.37* (.33)	.40** (.37*)	.37* (.34*)	–			
Dot comparison	.23 (.10)	.41** (.28)	.40* (.30)	.40* (.32*)	.15 (.06)	–.03 (–.12)	–		
Number Line	.15 (–.004)	.12 (-.06)	.60** (.54**)	.56**(.51**)	.27 (.20)	.29 (.24)	.51** (–.41)	–	
Stop signal task	–.17 (–.13)	–.26 (-.23)	–.06 (.02)	.17 (.22)	.32* (.36*)	.12 (.15)	–.06 (–.01)	.23 (.31)	–

Results

Descriptive statistics for overall performance on each task are displayed in Table 2. The correlations between the tasks are presented in Table 3. As a preliminary analysis, we compared choice reaction times between the DD and control groups (including performance on the correct trials only). Mean choice RTs were not significantly different between groups (p = .130). Nevertheless, as there was a trend toward shorter RTs in the control group, we included choice RT as a covariate in some of our analyses.

Order processing tasks

First we analyzed the results regarding the *parental order processing questionnaire*. The average score of the children in the DD and control groups were significantly different [$t(38)$ = 2.42 p = .021, Cohen's d = 0.76], indicating worse everyday ordering skills in the case of children with DD.[5]

Then we investigated performance on the order memory tasks. In the case of the *order working memory task*, children with DD had an average serial order memory span of 3.85 items. Children in the control group had an average order memory span of 4.40 items. The difference between groups in the total number of correctly recalled sequences was significant [$t(38)$ = 2.78 p = .008, Cohen's d = 0.88].

In the case of the *backward matrices task*, children with DD had an average visual-spatial working memory span of 5.75, whereas the control children had an average order memory span of 6.05 items. There was a significant difference between groups in the total number of correctly recalled sequences [$t(38)$ = 2.13 p = .040, Cohen's d = 0.76].

In the case of this task, it was also possible to compare the number of correctly recalled item locations between the two groups (i.e., when children recalled the right locations within a sequence, but not in the correct order). Out of 70 item locations, DD participants correctly recalled on average 62.20 (SD = 2.88), and the control participants recalled 62.45 (SD = 2.70), which showed that accuracy was high (about 89%) and not significantly different between the two groups (p = .779). That is, there was a group difference in memory for order, but not in item memory on this task.

We then analyzed performance on the *order judgment tasks*. We included the results of the number and annual event ordering tasks in the same analyses because we expected similar distance effects on each task. However, we considered the results separately for correct order and mixed-order trials (i.e., trials in which items were not shown in the correct order), because we expected the distance effects to be different across these trials. This grouping of the results was supported by the strong correlations between performance on the two tasks, both for correct order trials [$r(38) = 0.61$, $p < .001$] and for mixed-order trials [$r(38) = .42$, $p = .007$], whereas the correlations between correct order and mixed-order trials within each task were weaker and non-significant at this sample size (rs < .19). We analyzed the results separately for accuracy and RTs.

Regarding accuracy on the correct order trials (Figure 1), a 2 × 6 × 2 mixed ANOVA with task (number/event ordering) and distance between the two extreme items in the triad (2/3/4/5/6/7) as within-subjects factors, and group (DD/control) as a between-subjects factor indicated a significant effect of distance [$F(3,126) = 6.26$, $p < .001$, $\eta_p^2 = 0.14$], and a significant effect of task [$F(1,38) = 14.59$, $p < .001$, $\eta_p^2 = 0.28$], but no significant effect of group, and no significant interactions (ps > .190). The effect of task was present because accuracy was higher in the case of the number ordering task (M = 0.80, SD = 0.29) than in the case of the annual event ordering task (M = 0.65, SD = 0.29). Follow-up analyses using Bonferroni-Holm corrections indicated that accuracy for trials with a distance of 2 was significantly higher than for trials with distances of 4, 6 and 7. All other contrasts were non-significant.

A similar analysis of RTs showed only a significant effect of task [$F(1,38) = 14.59$, $p < .001$, $\eta_p^2 = 0.28$], with shorter RTs for the number ordering task (M = 2,911 ms, SD = 1,185 ms) than for the annual event ordering task (M = 3,981 ms, SD = 1,902 ms).

In summary, both the accuracy and RT results indicated that participants found the annual event ordering task more difficult than the number ordering task. Additionally, the accuracy results indicated a reverse distance effect in the case of both tasks.

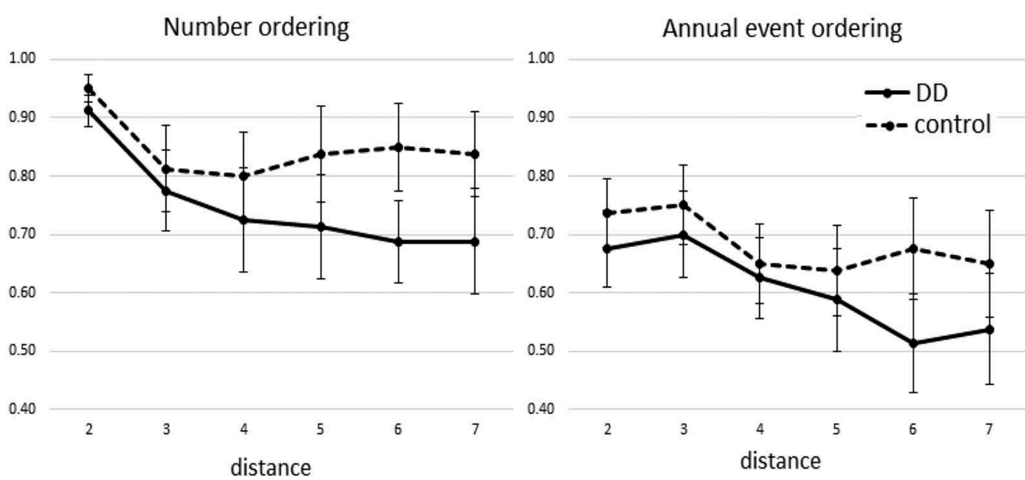

Figure 1. Accuracy on the number ordering and annual event ordering tasks in the case of correctly ordered trials, as a function of group and distance (error bars represent the standard error of the mean).

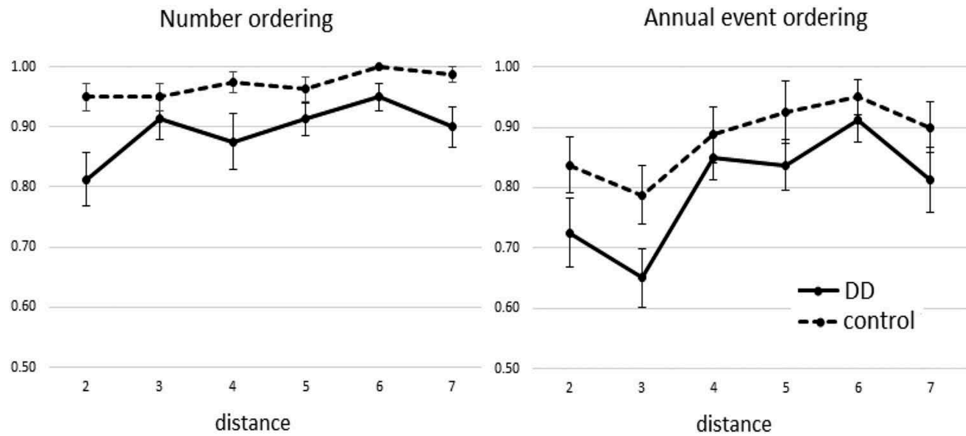

Figure 2. Accuracy on the number ordering and annual event ordering tasks in the case of mixed-order trials as a function of group and distance (error bars represent the standard error of the mean).

Regarding accuracy on the mixed-order trials (Figure 2), a 2 × 6 × 2 mixed ANOVA with task (number/event ordering) and distance between the two extreme items (2/3/4/5/6/7) as within-subjects factors, and group (DD/control) as a between-subjects factor indicated a significant effect of distance [$F(5,190) = 9.58$, $p < .001$, $\eta_p^2 = 0.20$], a significant effect of task [$F(1,38) = 21.18$, $p < .001$, $\eta_p^2 = 0.36$], and a significant effect of group [$F(1,38) = 9.48$, $p = .004$, $\eta_p^2 = 0.20$]. There was also a significant distance by task interaction [$F(5,190) = 3.50$, $p = .005$, $\eta_p^2 = 0.08$]. None of the other interaction effects were significant (*p*s > .540). The effect of task was present, because accuracy was higher in the case of the number ordering task ($M = 0.93$, $SD = 0.08$) than in the case of annual event ordering ($M = 0.84$, $SD = 0.14$). The group effect indicated that accuracy was lower in the DD group ($M = 0.85$, $SD = 0.10$) than in the control group ($M = 0.93$, $SD = 0.06$).

In order to follow up on the distance by task interaction, we ran separate one-way ANOVAs for each task with distance (2/3/4/5/6/7) as a within-subjects factor. In the case of the number ordering task, there was a significant effect of distance [$F(4, 143) = 2.70$, $p = .037$, $\eta_p^2 = 0.07$]. Follow-up analyses with Bonferroni-Holm corrections indicated that accuracy for trials with a distance of 2 was significantly lower than the accuracy of trials with a distance of 6.

Regarding the annual event ordering task, a similar analysis indicated a significant effect of distance ($F(5, 195) = 8.28$, $p < .031$, $\eta_p^2 = 0.18$). Follow-up analyses with Bonferroni-Holm corrections indicated that accuracy for trials with a distance of 2 were significantly lower than for trials with a distance of 6. Additionally, accuracy for trials with a difference of 3 was significantly lower than for trials with distances of 4, 5, 6 and 7.

In summary, the accuracy results on the mixed-order trials showed that participants found the annual event ordering task more difficult than the number ordering task, which was similar to the results regarding correct order trials. There was also a significant *canonical* distance effect on both tasks, with a stronger effect in the case of annual event ordering. Additionally, DD children performed more poorly on both tasks.

We also analyzed RTs on the mixed-order trials. A 2 × 6 × 2 mixed ANOVA with task (number/event ordering) and distance (2/3/4/5/6/7) as within-subjects factors, and group (DD/control) as a between-subjects factor indicated a significant effect of task ($F(1,38) = 15.56$, $p < .001$, $\eta_p^2 = 0.29$), with shorter RTs for number ordering (M = 2,847 ms, SD = 1,112 ms) than for annual event ordering (M = 3,822 ms, SD = 1,809 ms). There was also a significant task by group interaction [$F(1,38) = 5.34$, $p = .026$, $\eta_p^2 = 0.12$], and a marginal effect of distance ($p = .083$). The task by group interaction remained significant ($p = .022$) when the analysis was re-run with choice RT as a covariate. Follow-up analyses with Bonferroni-Holm corrections indicated that the RT difference between groups was significant in the case of the number ordering task (M = 3,242 ms, SD = 1,179 ms, for the DD group and M = 2,452 ms, SD = 904 ms, in the case of the control group), but it was not significant in the case of the annual event ordering task (M = 3,635 ms, SD = 1,939, for the DD group and M = 4,008 ms, SD = 1,699 ms, in the case of the control group). When choice RT was included as a covariate in the analysis of group differences on the number ordering task, the effect was slightly reduced (p = .044), and was no longer significant after applying Bonferroni-Holm corrections. The RT results on the mixed-order trials were in line with the previous results in showing that participants found the annual event ordering task more difficult than the number ordering task. Additionally, the task by group interaction indicated that children in the DD group tended to respond slower in the case of number ordering trials than controls, whereas the two groups had similar RTs in the case of the annual event ordering task.

Magnitude comparison and estimation tasks

We analyzed accuracy on the *symbolic comparison task* using a 6 × 2 mixed ANOVA with numerical distance (1/2/3/4/5/6) as a within-subjects factor, and group (DD/control) as a between-subjects factor (Figure 3). There was a significant main effect of distance [$F(1,57) = 6.92$ $p < .001$ $\eta_p^2 = 0.15$), but no effect of group (p = .253), and no distance by group interaction (p = .538). Follow-up analyses, using Bonferroni-Holm corrections indicated that there was a significant difference between accuracy for items with a numerical distance of 1 and items with a numerical distance of 4. Additionally, there was a significant difference between items with a numerical distance of 2 and items with numerical distances of 4, 5 and 6.

We also analyzed RTs on the *symbolic comparison task* using a 6 × 2 mixed ANOVA with numerical distance (1/2/3/4/5/6) as a within-subjects factor, and group (DD/control) as a between-subjects factor. There was a significant main effect of group [$F(1, 38) = 5.16$ $p = .029$ $\eta_p^2 = 0.12$), with

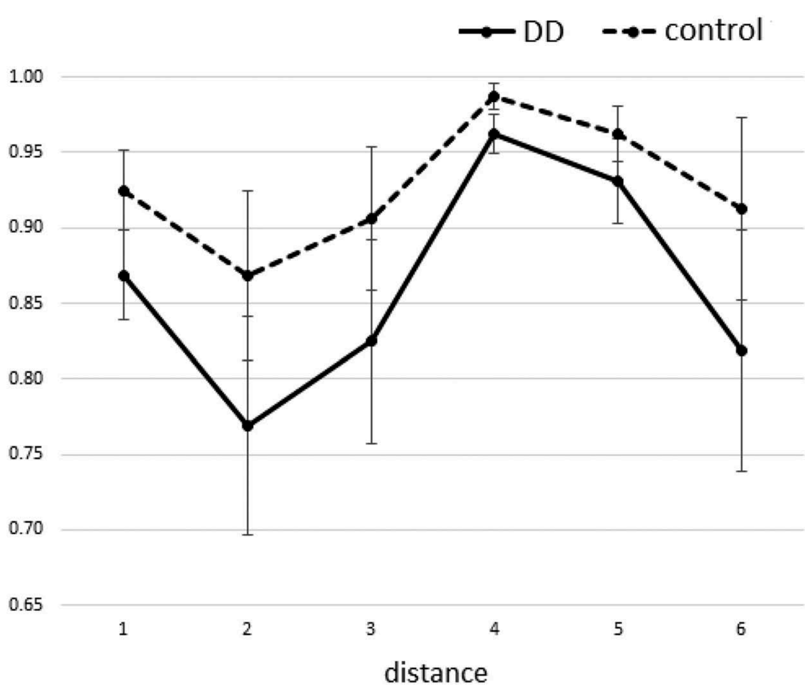

Figure 3. Accuracy on the symbolic comparison task as a function of distance and group (error bars represent the standard error of the mean).

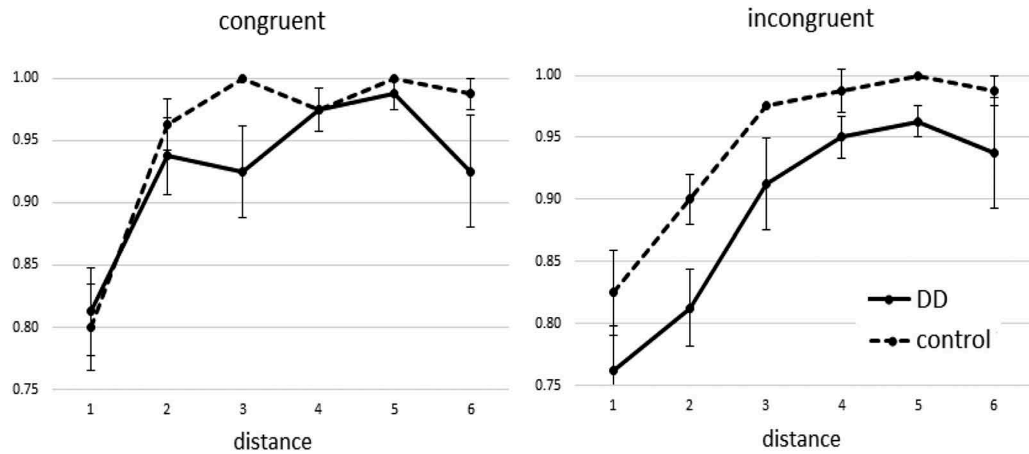

Figure 4. Accuracy on the nonsymbolic comparison task as a function of distance, congruency, and group (error bars represent the standard error of the mean).

children with DD responding more slowly (M = 1,276 ms, SD = 552 ms) than controls (M = 964 ms, SD = 267 ms). There was also a marginal effect of distance (p = .083), but there was no distance by group interaction (p = .757). When we repeated the ANOVA analysis including choice RT as a covariate, we found that the effect of choice RT was significant [$F(1, 37) = 5.68$ $p = .022$ $\eta_p^2 = 0.13$], whereas the effect of group was reduced to marginal (p = .088).

We analyzed accuracy on the *nonsymbolic comparison task*, using a 6 × 2 × 2 mixed ANOVA with numerical distance between the displays (1/2/3/4/5/6) and congruency between the surface area of the objects and numerosity (congruent/incongruent) as within-subjects factors, and group (DD/control) as a between-subjects factor (Figure 4). There was a significant effect of distance [$F(3, 123) = 28.59$, $p < .001$, $\eta_p^2 = 0.43$] and a significant effect of group [$F(1, 38) = 8.10$, $p = .007$, $\eta_p^2 = 0.18$], with lower accuracy in the DD group (M = 0.91, SD = 0.06) than in the control group (M =0 .95, SD = 0.03).[6] There was also a marginal effect of congruency (p = .051), but the interaction effects were not significant (ps > .20). Pairwise comparisons using Bonferroni-Holm corrections showed that accuracy for trials with a numerical distance of 1 was significantly lower than for trials with numerical distances of 2, 3, 4, 5 and 6. Additionally, accuracy for trials with a numerical distance of 2 was significantly lower than for trials with numerical distances of 4 and 5. All other comparisons yielded non-significant results.

We also analyzed performance on the *number line task*. We ran a 2 × 2 mixed ANOVA to investigate the effect of scale type (0–100/0–1000) as a within-subjects factor and group (DD/control) as a between-subjects factor. There was a significant effect of scale type [$F(1, 38) = 70.38$ $p < .001$ $\eta_p^2 = 0.65$], which was present, because the average estimation error for the 0–100 scale (M = 59.65, SD = 36.46) was smaller than for the 0–1000 scale (M = 148.24, SD = 73.09). Additionally, there was also a significant effect of group [$F(1, 38) = 7.79$ $p = .008$ $\eta_p^2 = 0.17$] with larger average error in the DD group (M = 123.19, SD = 48.55) than in the control group (M = 84.70, SD = 38.02). The scale type by group interaction was non-significant (p = .452).

Inhibition

In the case of the stop signal task, we first compared the DD and control groups on go trial accuracy in the case of blocks 3 and 4, where stop and go trials were mixed to check that children in both groups engaged with the task (i.e., that they pressed the button within the allocated time window of 1000 ms). Mean accuracy in the DD group was .80 (SD = 0.14) and it was .83 (SD = 0.22) in the

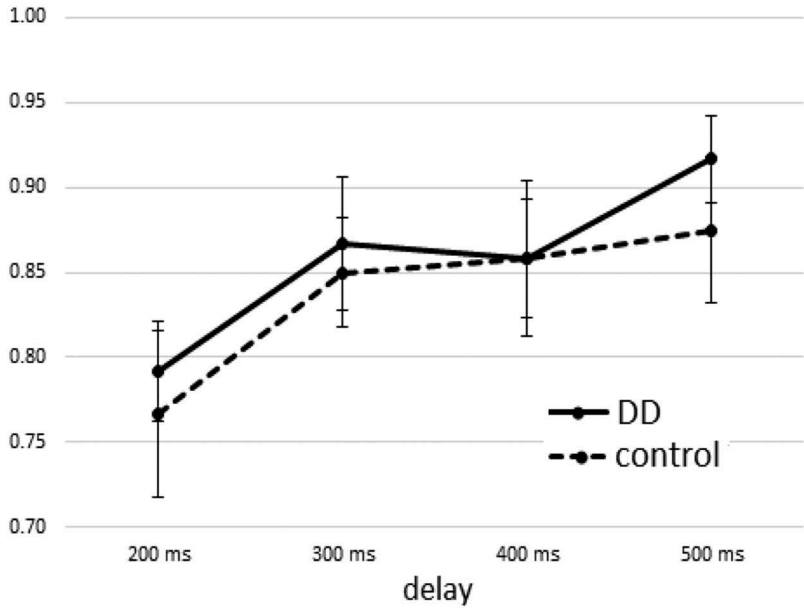

Figure 5. Accuracy on the stop signal task as a function of tone delay and group (error bars represent the standard error of the mean).

control group (p = .622). We analyzed the results regarding the “stop” trials using a mixed 2 × 4 ANOVA with stop signal delay (200/300/400/500 ms) as a within-subjects factor, and group (DD/control) as a between-subjects factor (see results in Figure 5). There was a significant effect of tone delay [$F(2.37, 89.88) = 17.24$ $p < .001$ $\eta_p^2 = 0.31$], but no main effect of group, and no interaction between tone delay and group ($ps > .35$). Follow-up analyses showed that performance at 200 ms delay was significantly worse than performance at all other delays, and performance at 300 ms delay was significantly worse than performance at 500 ms delay. The other comparisons were non-significant after applying a Bonferroni-Holm correction.

Best predictors of group membership

For diagnostic purposes, it is important to identify tasks that can reliably discriminate between individuals with and without DD. Given that there were several tasks that reliably discriminated between the two groups, we were interested in selecting the best predictors of group membership from this set of tasks. For this reason, we carried out a stepwise logistic regression analysis (using the forward conditional method), with group membership (DD/control) as the dependent variable, and total scores on the parental order processing questionnaire, the order working memory and backward matrices tasks, as well as accuracy scores on the annual events, number ordering and dot comparison tasks, and average error on the number line task as predictor variables (i.e., we only considered tasks where we found a significant group difference). The forward conditional method enters variables on the basis of their level of significance (Wald), and performs removal testing based on the probability of a likelihood-ratio statistic based on conditional parameter estimates (i.e., variables are removed if this does not result in a significant drop in the proportion of variance explained by the model). The stepwise method was chosen because we wanted to obtain a model that only included significant predictors. This method also offers a way to deal with multicollinearity as the contribution of each variable is considered one by one (Tabachnick & Fidell, 2007). In our model, multicollinearity was a potential problem, because of the strong correlations between some of the tasks.[7] Table 4 presents the order of entering the

Table 4. Logistic regression models with group membership (DD/control) as a dependent variable.

	Variables in the equation	*B*	Sig.	Model if variable removed		
				Model log likelihood	*Δ*-2 Log	Sig. of the change
Model 1	Dot comparison	26.14	.024	−27.78	8.68	.003
Model 2	Parental questionnaire	.10	.050	−23.48	4.47	.034
	Dot comparison	28.95	.032	−25.12	7.76	.005
Model 3	Order working memory	.51	.021	−21.37	8.51	.004
	Parental Questionnaire	.17	.015	−21.56	8.89	.003
	Dot comparison	24.26	.116	−18.80	3.37	.066
Model 4	Order working memory	.60	.009	−25.22	13.03	< .001
	Parental questionnaire	.19	.008	−24.13	10.85	.001
Model 5	Order working memory	.64	.011	−21.72	13.71	< .001
	Parental questionnaire	.24	.016	−20.80	11.89	.001
	Number line	−.04	.031	−19.20	8.68	.003

Overall model evaluation (Model 5): Likelihood ratio test: $\chi2 = 25.73$, $df = 3$, $p < .001$. Goodness-of-fit test: Hosmer & Lemeshow: $\chi2 = 9.56$, $df = 8$, $p = .298$; Nagelkerke $R^2 = .63$.

predictors into the regression equation, the contribution of each variable, and change in the explained variance if a variable is removed. The final model, which explained the greatest proportion of variance (Nagelkerke $R^2 = 0.63$), included the following predictors: order working memory, parental questionnaire and the number line task. This model categorized 80% of the participants correctly as DD/control (Table 5). Interestingly, model 4, which only included order working memory and the parental questionnaire, performed even better in categorizing the participants (with 82.5% categorized correctly), although the amount of variance explained by this model (Nagelkerke $R^2 = 0.48$) was significantly lower than the variance explained by model 5.[8]

Discussion

Results regarding order processing

The main aim of this study was to test the hypothesis that DD involves order processing deficits using the broadest range of order processing measures so far. These included some novel measures that have never been used in the case of participants with DD before: a questionnaire on everyday ordering abilities, and an annual event ordering task. Our results supported the hypothesis that children with DD have order processing difficulties, including problems with everyday activities that require ordering (e.g., recalling the order in which past events happened), recalling short, novel sequences (of both verbal materials and spatial locations), and making judgments about the

Table 5. Number and proportion of participants correctly identified by each logistic regression model.

	Observed	Predicted		Percentage correct classification
		DD	Control	
Model 1	DD	10	10	50
	Control	6	14	70
	Overall percentage			60
Model 2	DD	14	6	70
	Control	6	14	70
	Overall percentage			70
Model 3	DD	15	5	75
	Control	3	17	85
	Overall percentage			80
Model 4	DD	16	4	80
	Control	3	17	85
	Overall percentage			82.5
Model 5	DD	17	3	85
	Control	5	15	75
	Overall percentage			80

correctness of the order of familiar sequences (including both numerical and non-numerical items) that draw on long-term memory representations.

In the case of memory for unfamiliar/novel sequences, the verbal task did not require memory for items (i.e., the task was a pure measure of order memory). The spatial task required memory for locations and order as well. In the case of this task, we have confirmed that children with DD recalled locations just as accurately as controls, but they showed impaired memory for order. This extends the findings of Attout and Majerus (2014) who showed impaired order memory, but intact item memory for verbal materials in DD.

With regard to order judgments about familiar sequences, our materials were designed in such a way that a direct comparison was possible between numerical and non-numerical sequences. Earlier studies showed similar (reverse) distance effects in the case of ordered sequences of numbers, letters and months (e.g., Goffin & Ansari, 2016; Jou & Aldridge, 1999; Lyons & Beilock, 2013; Morsanyi et al., 2017; Turconi, Campbell, & Seron, 2006; Vos et al., 2017). When present, canonical distance effects had been found in the case of mixed-order sequences of both sorts of familiar items, and reverse distance effects had been found in the case of correctly ordered sequences.[9] In order to investigate these effects, we analyzed distance effects on correctly ordered and mixed-order trials separately. A key question regarding these tasks was whether there was any evidence that DD children show specific deficits in numerical order judgments (which are distinct from their order judgments regarding annual events).

As expected, children with DD performed more poorly on these order judgment tasks than controls. Specifically, they were less able to recognize when the order of items within a triad was incorrect. Importantly, this effect was present in the case of both number and event ordering. Additionally, although the annual events task was more difficult for children, as indicated by both the accuracy and RT results, the distance effects were remarkably similar across tasks, with reverse distance effects in the case of correct order trials, and canonical distance effects in the case of mixed-order trials. Importantly, the distance effects were also similar across groups. The only result that hinted at any domain-specific effect was the finding that the RT difference between groups was larger in the case of mixed-order trials on the number ordering task than in the case of the annual event ordering task. Nevertheless, this group difference was not reliable after controlling for basic RT.

In summary, the results of the ordering tasks showed strong evidence for ordering deficits in DD (indeed, the effect sizes for group differences were generally large, and a non-significant difference was only found in one case: for correctly ordered trials in the number and event ordering tasks). Thus, the results were similar across a broad range of measures. Importantly, most of these did not include numbers, and when number ordering was compared to an annual event ordering task, the results were very similar, both in terms of group differences across the two tasks and distance effects. These results strongly suggest that ordering deficits in DD are not restricted to the domain of numbers (see also Attout & Majerus, 2014; Attout, Salmon & Majerus., 2015 De Visscher et al., 2015; Rubinsten & Sury, 2011).

Magnitude comparison and estimation

In addition to the investigation of ordering ability in DD, we also administered a series of tasks to measure magnitude comparison and estimation skills. There were clear group differences in the case of two tasks: the non-symbolic comparison task and the number line task. The non-symbolic comparison task that we used was similar to the task used by Price et al. (2007), although our task was not designed to investigate RTs. We found similar distance effects on the task as Price et al. (2007). However, we did not find a group by distance interaction. Instead, we found a main effect of group, with DD children performing more poorly on the task across all distances. As the distance effect was large, it is unlikely that we did not detect the interaction effect due to a lack of statistical power. In fact, the distance by group interaction was very far from being significant (p = .651). Thus, although children with DD were less accurate in their magnitude comparison judgments, the pattern of results did not suggest that DD and control children relied on different response strategies.

As we noted in the introduction, there is inconsistency in the literature regarding dot comparison performance in dyscalculia. A possible issue to consider is that there is evidence that the way the stimuli are designed have a strong effect on performance on the task (e.g., Szucs, Nobes et al., 2013). Although most of this literature is focussed on the way visual stimulus parameters are manipulated in the task, the numerosity of the dots that are presented might also be important. There is evidence that the estimation of small and larger numerosities is based on different processes. Burr, Anobile and Arrighi (2017) presented psychophysiological evidence that there are three different mechanisms involved in numerosity processing, depending on the number and perceptual properties of the items. Separate mechanisms are used in the subitizing range (up to about four items), in the small numerosity range (from about five items up to about 30 items, depending on the density of the display), and when a larger number of items are presented, in particular when these items merge into a texture. According to Burr et al. (2017), only estimation skills in the small numerosity range are related to mathematics abilities in typical participants.

Some previous studies that showed a difference in dot comparison performance between DD and control participants included stimuli in the small numerosity range (e.g., Mazzocco et al., 2011; Piazza et al., 2010), whereas other studies used stimuli in both the subitizing and the small numerosity ranges (Mussolin et al., 2010; Price et al., 2007; Skagerlund & Träff, 2016). The latter studies included tasks that used small numbers between 1 and 9, which is similar to the numbers typically presented in symbolic comparison tasks. In our task, we also used between 1 and 9 items, which covers both the subitizing and the small numerosity ranges (a typical display included a mixture of both). This leaves the question open whether comparison performance in DD is affected in both ranges (although see Ashkenazi, Mark-Zigdon, & Henik, 2013 for a related study that showed impairments in both ranges in DD in an enumeration task).

The logistic regression results also offer interesting insight into whether this task is useful in discriminating between dyscalculic and control participants. This task was entered first into the regression equation (model 1), on the basis that among all individual predictors, the regression coefficient of this task was associated with the lowest *p* value. Nevertheless, looking at the results in Table 5, it can be seen that on the basis of their performance on this task, participants with DD were categorized as dyscalculic with 50% probability (i.e., the model performed at chance).[10] Thus, the task was somewhat useful in identifying participants who were *not* dyscalculic, but the results indicate that low performance on this task was only present in some participants with DD (i.e., low performance was not generally characteristic of this group). This is in contrast with the performance of model 4, which included two ordering tasks, and performed very successfully at correctly identifying both DD and control participants.

In the case of the number line task, there was once more a group effect (see also Skagerlund & Traff, 2016), as well as an effect of scale type. Specifically, children's judgments of the position of numbers were more accurate in the case of the 0–100 scale than in the case of the 0–1000 scale, although the two scales were of equal physical length. This suggests that the difference between the accuracy of judgments across scales was related to children's cognitive representations of the number sequences (i.e., more precise representations in the case of smaller numbers), rather than to the way they had to respond to the task. Importantly, we did not find an interaction effect between scale type and group (the effect was non-significant with a very small effect size), which again indicated that the underlying cognitive processes across groups were similar, although children with DD performed more poorly on these tasks.

A final task related to magnitude processing was the symbolic comparison task. Once more, we found similar distance effects in the two groups (see also Soltész et al., 2007), suggesting that they processed the stimuli in the same way. Additionally, there was a difference in RTs between the two groups. Nevertheless, once we controlled for choice RTs, the group difference in RTs was reduced to a non-significant trend. The results regarding the symbolic comparison task are in line with Szucs, Devine et al., 2013 but they are in contrast with Rousselle and Noël (2007) who reported group differences on the symbolic comparison task, both for accuracy and RTs.

In summary, group differences were found in the case of the non-symbolic comparison task and the number line task, whereas the evidence for a difference in symbolic comparison performance was weak. As in the case of the order processing tasks, the group differences appeared to be related to the efficiency of processing, rather than to qualitative differences in the way children with DD and controls responded to the tasks.

Inhibition

Inhibition skills are important for mathematics (e.g., Bull & Scerif, 2001; St Clair-Thomson & Gathercole, 2006; Blair & Razza, 2007), and Szucs, Devine et al., 2013 proposed that impairments in inhibition skills might be a defining feature of DD. Additionally, recent studies (e.g., Fuhs & McNeil, 2013; Gilmore et al., 2013; Szűcs, Nobes, Devine, Gabriel, & Gebuis, 2013) suggested that the link between performance on non-symbolic comparison tasks and mathematics skills might be attributable to the inhibition component of the task, and could be restricted to incongruent trials (although see Keller & Libertus, 2015). Szucs, Devine et al., 2013 also reported a group by congruency interaction when they compared children with DD and controls, with larger congruency effects in the case of children with DD. For these reasons, we were interested in potential group differences in congruency effects in the non-symbolic comparison task. In contrast with Szucs, Devine et al., 2013 but in line with Rousselle and Noël (2007), we found no significant interaction between congruency and group (p = .207), and this effect was not only non-significant, but also small in size (η_p^2 = 0.048). Nevertheless, it is important to note that the studies that found that incongruent trials were more predictive of mathematics ability than congruent trials all used non-symbolic comparison tasks with a relatively large number of items within the arrays that they presented. Thus, it is possible that we did not replicate these findings because we used arrays with a small number of items, which might rely on different cognitive processes (Burr, Anobile, & Arrighi, 2018).

We also did not find evidence of group differences in response inhibition, as measured by the stop signal task. Indeed, the pattern of responses, and the effect of stop signal delay was very similar across groups. These results are in contrast with Szucs, Devine et al., 2013 who found a difference between groups in stop signal accuracy, as well as a greater effect of congruency in the DD group than in the case of controls.

Ordering vs. magnitude processing

Rubinsten and Sury (2011) proposed that magnitude and order processing are two independent core systems, and ordering in particular is impaired in dyscalculia. Although in our sample of children with dyscalculia, we have found evidence for both ordering and magnitude processing/estimation deficits, the results of the regression analysis showed that children with dyscalculia could be identified with high precision on the basis of their performance on some ordering tasks alone (specifically, the parental ordering questionnaire and the order memory task). In fact, among the magnitude/estimation tasks, the number line task was the best predictor of group membership. Interestingly, the number line task has been described as a task that combines the need for estimation and magnitude-processing skills with an understanding of ordinality (cf., Kaufmann & von Aster, 2012; von Aster & Shalev, 2007).

Regarding the notion of the independence of magnitude processing and ordering skills, some recent papers showed a close link between these skills (e.g., Lyons & Beilock, 2011; Morsanyi et al., 2017; Sasanguie et al., 2017), although these studies also showed that there was only a partial overlap between ordering and magnitude processing skills. Our finding that ordering and magnitude processing deficits co-occur in DD also hint at the possibility that these skills are inherently related. Nevertheless, order processing problems were the best predictors of a diagnosis of DD.

Domain-specific vs. domain-general deficits in developmental dyscalculia

Whereas much research has focussed on domain-specific impairments in dyscalculia, recent findings, as well as clinical observations, point to more general deficits that extend beyond the domain of numbers. Specifically, DD has been linked to the impairments of order memory (Attout & Majerus, 2014; Attout, Salmon et al. 2015 as well as visual-spatial memory (Mammarella et al., 2015; Szűcs et al., 2014). Szucs, Devine et al., 2013 also reported inhibition impairments in non-numerical tasks in DD. Morsanyi, Devine, Nobes, and Szucs, Devine et al., 2013 presented evidence for impaired verbal reasoning skills in DD, using transitive reasoning tasks.[11] It is notable that, with the exception of the tasks measuring inhibition skills, all of these tasks include the requirement to process information about order (although the specific order processing component of the tasks has not always been isolated). Clinical descriptions of DD also highlight problems with order-processing/sequencing outside the numerical domain.

The current results extend these findings by showing, in particular, that children with DD have ordering difficulties in the domain of time (e.g., remembering the order of past events, carrying out a sequence of actions, making judgments about the order of annual events, etc.). This has important implications for interventions for DD. First, children with DD might not only need support with mathematics, but also with being better orientated in time. Indeed, these skills could be very important for the everyday functioning of individuals with DD. Second, non-numerical order training might be useful in making intervention approaches more diverse, and less stressful to children who already accumulated negative experiences with mathematics. In particular, practicing non-numerical ordering skills might be less intimidating, as children do not associate them with academic success.

Limitations and future directions

The current results provide strong evidence for ordering deficits in DD. However, some limitations of our study should be mentioned. One issue is the size of the groups. Although we made every effort to recruit a large sample of participants, and initially screened over 3,000 children, we were only able to identify 20 children with a profile of very low mathematics skills in the absence of low IQ and significant difficulties with reading. Indeed, these children also had relatively low IQ and reading skills, although their scores were within the normal range.

Another limitation is that, as our main focus was on order processing, it can be argued that we did not pay equal attention to other skills, such as magnitude processing/estimation abilities and inhibition skills. Regarding magnitude processing/estimation, we have specifically selected three tasks that were previously used with DD participants, and that we had good reasons to expect to show performance differences between DD and control children. Indeed, this was confirmed for both the dot comparison and the number line task. Nevertheless, future studies could compare performance on multiple versions of the dot comparison task, also varying the number of items and using different ways to control the perceptual properties of the tasks, to further investigate both estimation abilities and susceptibility to perceptual distractors in DD. Inhibition skills in DD could also be investigated using Stroop tasks.

Regarding the ordering tasks, the correlations between these tasks ranged from weak and non-significant to very strong. Thus, it is likely that although all of these tasks share an ordering/sequencing component, the underlying processes are only partially overlapping. In fact, within the number and event ordering tasks, there was also a dissociation between performance on correctly ordered and mixed-order trials, and the group difference was only present for the latter. Thus, an important future direction could be to investigate the cognitive processes that are implicated in these tasks further.

It is also important to note that, when selecting the participants (in both the DD and the control group), we have excluded all children with an official diagnosis of a developmental disorder. This was useful for specifically investigating the effects of mathematics difficulties. Nevertheless, dyscalculia is a heterogeneous condition (e.g., Kaufmann et al., 2013; Rubinsten & Henik, 2009) and comorbidity with other developmental disorders is very common. Thus, it is likely that the cognitive profile of some children with DD will differ from the typical profile identified in this study.

Conclusions

This study compared the performance of children with DD and children without mathematics difficulties on a range of tasks assessing ordering skills, magnitude processing/estimation skills, and inhibition. The two groups were closely matched on age, gender, socio-economic status, educational experiences, IQ and reading ability. The findings revealed differences between the groups both in ordering and magnitude processing abilities. Specifically, both numerical and non-numerical ordering skills were impaired in DD, as well as performance on the dot comparison and number line tasks. Nevertheless, these differences appeared to be quantitative, rather than qualitative, as distance effects, as well as other within-task manipulations had the same effect on the performance of both groups. A logistic regression analysis indicated that a combination of the parental ordering questionnaire, order working memory and the number line task could be used to correctly identify 80% of the participants as dyscalculic or non-dyscalculic. Indeed, the ordering tasks alone identified a slightly larger proportion (82.5%) of participants correctly. This has great significance for the development of novel diagnostic methods for DD. In particular, because even very young children can perform some non-numerical ordering tasks, an early diagnosis of susceptibility to maths difficulties might be possible. The finding that both numerical and non-numerical ordering skills are impaired in dyscalculia extends the findings of previous investigations (Attout & Majerus, 2014; Attout et al., 2015; De Visscher et al., 2015; Kauffmann et al., 2011; Rubinsten & Sury, 2011). Indeed, the current study provided stronger evidence for non-numerical than numerical ordering deficits. We also presented a new parental questionnaire, and a novel task to measure non-numerical ordering skills (i.e., the annual events ordering task) that could be used in future studies. The current findings also open up new avenues for designing interventions for individuals with maths difficulties.

Notes

1. We note that some studies (e.g., Skagerlund & Träff, 2014; Vicario, Rappo, Pepi, Pavan, & Martino, 2012) have found impaired time estimation abilities in dyscalculia. However, this skill, which is likely to rely on separate specialized timing mechanisms, was not investigated in the current study.
2. Note that the nature of the involvement of inhibition processes in dot comparison performance is debated (see Keller & Libertus, 2015; various contributions in Henik, 2016).
3. The DSM-5 diagnostic criteria for dyscalculia/specific learning disorder in mathematics (in contrast with the DSM-IV criteria), do not require a discrepancy between maths scores and IQ. However, for the purposes of this study, we recruited children with a significant maths-IQ discrepancy, as this can help in disentangling the effects of low maths scores vs. low IQ on their performance on the tasks. We also did this so that we could obtain samples with IQs in the normal range. In terms of the individual profiles of the children in the DD group, in the case of 10 children, there was a discrepancy of at least seven standard points between both the children's IQ and reading scores and their maths scores (i.e., half of the children only had a difficulty in maths). There were four additional children who had a relatively large discrepancy between their IQ and maths scores, but only a small discrepancy between their maths and English scores (i.e., they had difficulties with both maths and English). Nevertheless, these children did not have a diagnosis of dyslexia, and, for this reason, we decided to keep them in our dyscalculia sample. In the case of the remaining 6 children, there was a large discrepancy between their maths and English scores, but only a small discrepancy between their maths and IQ scores. We decided to include these children in our sample on the basis that their sustained difficulties with maths did not extend to other aspects of learning. Although we acknowledge that this results in a DD group with a somewhat heterogeneous cognitive profile, this is quite common in the literature on dyscalculia. Regarding the profile of the control children, they did not represent very well a typical population. However, our aim was to maximize the differences in maths skills, while minimizing the differences in all other relevant factors between the children in the two groups.
4. This task was modeled on Morsanyi et al. (2017). A list of all trials can be found in the paper.
5. The group difference was also significant in a non-parametric statistical analysis, using a Mann-Whitney U test (p = .038).

6. It could be argued that, because performance was close to ceiling on this task, the ANOVA analyses were not appropriate. Nevertheless, the group difference was also present when we used a Mann-Whitney U test (p = .005). We preferred to present the results of the ANOVA analyses in the main text, because this is the typical analysis strategy in the relevant literature (e.g., Gilmore et al., 2014; Price et al., 2007).
7. Another way to deal with multicollinearity would be to combine the scores from highly correlated variables. However, for interpretative purposes, it is more useful to assess the individual contribution of each task.
8. The results regarding explained variance and the model's ability to identify participants as DD/control might seem contradictory. It might be useful to consider that model 4 was particularly successful at identifying participants who were *not* dyscalculic, whereas model 5 showed the best performance in identifying DD participants (i.e., correct classification is not additive, when a new variable is included in the model). In other words, overall explained variance in diagnostic status increases with each additional relevant predictor variable, however, the ability of the model to correctly identify an individual's diagnostic status will depend on the fit between each individual's profile and the profile predicted by the statistical model.
9. These effects indicate that in the case of correctly ordered trials, participants find it easier to recognize correct trials when the items immediately follow each other (e.g., 1 2 3), but they sometimes incorrectly reject trials where the items do not form a familiar sequence (e.g., 2 5 8). In the case of mixed-order trials, participants experience more difficulty on close trials (e.g., 2 4 3) – i.e., sometimes they incorrectly accept these.
10. For a comparison, on the basis of the parental questionnaire alone, 70% of the participants could be identified correctly as DD or control. Using the order working memory task or the number line task alone, 67.5% of the participants could be correctly classified.
11. An example for a transitive reasoning task is: "If bicycles are faster than aeroplanes, and cars are faster than bicycles, then are cars faster than aeroplanes?" This task involves the requirement to order items along a single continuum (in this case, according to how fast they are), and make judgments about the relative position of the items. Some of the tasks also require participants to accept premises that are unbelievable, which might require the inhibition of beliefs.

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Declaration of interest

The views expressed are those of the authors and not necessarily those of the Foundation. More information is available at www.nuffieldfoundation.org.

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References

Ashkenazi, S., Mark-Zigdon, N., & Henik, A. (2013). Do subitizing deficits in developmental dyscalculia involve pattern recognition weakness? *Developmental Science*, *16*, 35–46. doi:10.1111/j.1467-7687.2012.01190.x

Ashkenazi, S., Rubinsten, O., & Henik, A. (2009). Attention, automaticity, and developmental dyscalculia. *Neuropsychology*, *23*, 535–540. doi:10.1037/a0015347

Attout, L., & Majerus, S. (2014). Working memory deficits in developmental dyscalculia: The importance of serial order. *Child Neuropsychology*, *21*, 432–450. doi:10.1080/09297049.2014.922170

Attout, L., Salmon, E., & Majerus, S. (2015). Working memory for serial order is dysfunctional in adults with a history of developmental dyscalculia: Evidence from behavioral and neuroimaging data. Developmental Neuropsychology, 40, 230–247. DOI: 10.1080/87565641.2015.1036993

Attout, L., Noël, M. P., & Majerus, S. (2015). The relationship between working memory for serial order and numerical development: A longitudinal study. *Developmental Psychology*, *50*, 1667–1679. doi:10.1037/a0036496

Attout, L., Salmon, E., & Majerus, S. (2015). Working memory for serial order is dysfunctional in adults with a history of developmental dyscalculia: Evidence from behavioral and neuroimaging data. *Developmental Neuropsychology*, *40*, 230–247. doi:10.1080/87565641.2015.1036993

Blair, C., & Razza, R. P. (2007). Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child Development*, *78*, 647–663. doi:10.1111/j.1467-8624.2007.01019.x

Booth, J. L., & Siegler, R. S. (2006). Developmental and individual differences in pure numerical estimation. *Developmental Psychology*, *42*, 189–201. doi:10.1037/0012-1649.41.6.189

Booth, J. L., & Siegler, R. S. (2008). Numerical magnitude representations influence arithmetic learning. *Child Development*, *79*, 1016–1031. doi:10.1111/j.1467-8624.2008.01173.x

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: Inhibition, switching, and working memory. *Developmental Neuropsychology*, *19*, 273–293. doi:10.1207/S15326942DN1903_3

Burr, D. C., Anobile, G., & Arrighi, R. (2018). Psychophysical evidence for the number sense. Philosophical Transactions of the Royal Society B, 373(1740), 20170045. DOI: 10.1098/rstb.2017.0045.

Butterworth, B. (2005). Developmental dyscalculia. In J. I. D. Campbell (Ed.), *Handbook of mathematical cognition* (pp. 455–467). New York: Psychology Press.

De Smedt, B., & Gilmore, C. K. (2011). Defective number module or impaired access? Numerical magnitude processing in first graders with mathematical difficulties. *Journal of Experimental Child Psychology*, *108*, 278–292. doi:10.1016/j.jecp.2010.09.003

De Smedt, B., Verschaffel, L., & Ghesquière, P. (2009). The predictive value of numerical magnitude comparison for individual differences in mathematics achievement. *Journal of Experimental Child Psychology*, *103*, 469–479. doi:10.1016/j.jecp.2009.01.010

De Visscher, A., Szmalec, A., van der Linden, L., & Noël, M. P. (2015). Serial-order learning impairment and hypersensitivity-to-interference in dyscalculia. Cognition, 144, 38–48. DOI: 10.1016/j.cognition.2015.07.007.

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 626–641.

Espy, K. A., McDiarmid, M. M., Cwik, M. F., Stalets, M. M., Hamby, A., & Senn, T. E. (2004). The contribution of executive functions to emergent mathematic skills in preschool children. *Developmental Neuropsychology*, *26*, 465–486. doi:10.1207/s15326942dn2601_6

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology: General*, *133*, 101–135. doi:10.1037/0096-3445.133.1.101

Friedman, W. J. (1990). Children's representations of the pattern of daily activities. *Child Development*, *61*, 1399–1412. doi:10.1111/j.1467-8624.1990.tb02870.x

Friedman, W. J. (2000). The development of children's knowledge of the times of future events. *Child Development*, *71*, 913–932. doi:10.1111/1467-8624.00199

Friedman, W. J. (2002). Children's knowledge of the future distances of daily activities and annual events. *Journal of Cognition and Development*, *3*, 333–356. doi:10.1207/S15327647JCD0303_4

Fry, A. F., & Hale, S. (1996). Processing speed, working memory, and fluid intelligence: Evidence for a developmental cascade. *Psychological Science*, *7*, 237–241. doi:10.1111/j.1467-9280.1996.tb00366.x

Fuhs, M. W., & McNeil, N. M. (2013). ANS acuity and mathematics ability in preschoolers from low-income homes: Contributions of inhibitory control. *Developmental Science*, *16*, 136–148. doi:10.1111/desc.12013

Geary, D. C. (2004). Mathematics and learning disabilities. *Journal of Learning Disabilities*, *37*, 4–15. doi:10.1177/00222194040370010201

Geary, D. C. (2011). Cognitive predictors of achievement growth in mathematics: A 5-year longitudinal study. *Developmental Psychology*, *47*, 1539–1552. doi:10.1037/a0025510

Gilmore, C., Attridge, N., Clayton, S., Cragg, L., Johnson, S., Marlow, N., … Inglis, M. (2013). Individual differences in inhibitory control, not non-verbal number acuity, correlate with mathematics achievement. *PLOS ONE*, *8*(6), e67374. doi:10.1371/journal.pone.0067374

Gilmore, C., Attridge, N., De Smedt, B., & Inglis, M. (2014). Measuring the approximate number system in children: Exploring the relationships among different tasks. *Learning and Individual Differences*, *29*, 50–58. doi:10.1016/j.lindif.2013.10.004

Goffin, C., & Ansari, D. (2016). Beyond magnitude: Judging ordinality of symbolic number is unrelated to magnitude comparison and independently relates to individual differences in arithmetic. *Cognition*, *150*, 68–76. doi:10.1016/j.cognition.2016.01.018

Hannula, M. M., Lepola, J., & Lehtinen, E. (2010). Spontaneous focusing on numerosity as a domain-specific predictor of arithmetical skills. *Journal of Experimental Child Psychology*, *107*, 394–406. doi:10.1016/j.jecp.2010.06.004

Henik, A. (Ed.). (2016). *Continuous issues in numerical cognition: How many or how much*. New York: Academic Press.

Hitch, G. J., & McAuley, E. (1991). Working memory in children with specific arithmetical learning difficulties. *British Journal of Psychology*, *82*, 375–386. doi:10.1111/j.2044-8295.1991.tb02406.x

Iuculano, T., Tang, J., Hall, C. W., & Butterworth, B. (2008). Core information processing deficits in developmental dyscalculia and low numeracy. *Developmental Science*, *11*, 669–680. doi:10.1111/j.1467-7687.2008.00716.x

Jou, J., & Aldridge, J. W. (1999). Memory representation of alphabetic position and interval information. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*, 680–701. doi:10.1037/0278-7393.25.3.680

Kaufmann, L., Mazzocco, M. M., Dowker, A., von Aster, M., Goebel, S., Grabner, R., … Rubinsten, O. (2013). Dyscalculia from a developmental and differential perspective. *Frontiers in Psychology*, *4*, 516. doi:10.3389/fpsyg.2013.00516

Kaufmann, L., Vogel, S. E., Starke, M., Kremser, C., & Schocke, M. (2009). Numerical and non-numerical ordinality processing in children with and without developmental dyscalculia: Evidence from fMRI. Cognitive Development, 24, 486–494. DOI: 10.1016/j.cogdev.2009.09.001

Kaufmann, L., & von Aster, M. (2012). The diagnosis and management of dyscalculia. *Deutsches Ärzteblatt International*, *109*, 767–778. doi:10.3238/arztebl.2012.0767

Keller, L., & Libertus, M. (2015). Inhibitory control may not explain the link between approximation and math abilities in kindergarteners from middle class families. *Frontiers in Psychology*, *6*, 685. doi:10.3389/fpsyg.2015.00685

Kline, P. (2000). *A psychometrics primer*. London, UK: Free Association Books.

Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8–9-year-old students. *Cognition*, *93*, 99–125. doi:10.1016/j.cognition.2003.11.004

Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review*, *91*, 295–327. doi:10.1037/0033-295X.91.3.295

Lyons, I. M., & Ansari, D. (2015). Numerical order processing in children: From reversing the distance-effect to predicting arithmetic. *Mind, Brain, and Education*, 207–221. doi:10.1111/mbe.12094

Lyons, I. M., & Beilock, S. L. (2011). Numerical ordering ability mediates the relation between number-sense and arithmetic competence. *Cognition*, *121*, 256–261. doi:10.1016/j.cognition.2011.07.009

Lyons, I. M., & Beilock, S. L. (2013). Ordinality and the nature of symbolic numbers. *Journal of Neuroscience*, *33*, 17052–17061. doi:10.1523/JNEUROSCI.1775-13.2013

Lyons, I. M., Price, G. R., Vaessen, A., Blomert, L., & Ansari, D. (2014). Numerical predictors of arithmetic success in grades 1–6. *Developmental Science*, *17*, 714–726. doi:10.1111/desc.12152

Lyons, I. M., Vogel, S. E., & Ansari, D. (2016). On the ordinality of numbers: A review of neural and behavioral studies. *Progress in Brain Research*, *227*, 187–221. doi:10.1016/bs.pbr.2016.04.010

Majerus, S., Poncelet, M., Greffe, C., & van der Linden, M. (2006). Relations between vocabulary development and verbal short-term memory: The relative importance of short-term memory for serial order and item information. *Journal of Experimental Child Psychology*, *93*, 95–119. doi:10.1016/j.jecp.2005.07.005

Mammarella, I. C., Hill, F., Devine, A., Caviola, S., & Szűcs, D. (2015). Math anxiety and developmental dyscalculia: A study on working memory processes. *Journal of Clinical and Experimental Neuropsychology*, *37*, 878–887. doi:10.1080/13803395.2015.1066759

Mazzocco, M. M., Feigenson, L., & Halberda, J. (2011). Impaired acuity of the approximate number system underlies mathematical learning disability (dyscalculia). *Child Development*, *82*, 1224–1237. doi:10.1111/j.1467-8624.2011.01608.x

Morsanyi, K., Devine, A., Nobes, A., & Szűcs, D. (2013). The link between logic, mathematics and imagination. Evidence from children with developmental dyscalculia and mathematically gifted children. *Developmental Science*, *16*, 542–553. doi:10.1111/desc.12048

Morsanyi, K., McCormack, T., & O'Mahony, E. (2018). The link between deductive reasoning and mathematics. *Thinking & Reasoning*, *24*, 234–257. doi:10.1080/13546783.2017.1384760

Morsanyi, K., O'Mahony, E., & McCormack, T. (2017). Number comparison and number ordering as predictors of arithmetic performance in adults: Exploring the link between the two skills, and investigating the question of domain-specificity. *The Quarterly Journal of Experimental Psychology*, *70*, 2497–2517. doi:10.1080/17470218.2016.1246577

Morsanyi, K., van Bers, B. M. C. W., McCormack, T., & McGourty, J. (2018). The prevalence of specific learning disorder in mathematics and comorbidity with other developmental disorders in primary school age children. *British Journal of Psychology*, *(in press)*. doi:10.1111/bjop.12322

Mussolin, C., Mejias, S., & Noël, M. P. (2010). Symbolic and nonsymbolic number comparison in children with and without dyscalculia. *Cognition*, *115*, 10–25. doi:10.1016/j.cognition.2009.10.006

National Center for Learning Disabilities (2007). Understanding dyscalculia. Retrieved from: http://www.ldonline.org/article/13709/

O'Connor, P. A., Morsanyi, K., & McCormack, T. (2018). Young children's non-numerical ordering ability at the start of formal education longitudinally predicts their symbolic number skills and academic achievement in math. (in press). doi:10.1111/desc.12645

Passolunghi, M. C., & Siegel, L. S. (2001). Short-term memory, working memory, and inhibitory control in children with difficulties in arithmetic problem solving. *Journal of Experimental Child Psychology*, *80*, 44–57. doi:10.1006/jecp.2000.2626

Passolunghi, M. C., & Siegel, L. S. (2004). Working memory and access to numerical information in children with disability in mathematics. *Journal of Experimental Child Psychology*, *88*, 348–367. doi:10.1016/j.jecp.2004.04.002

Piazza, M. Facoetti, A., Trussardi, A.N., Berteletti, I., Conte, S., Lucangeli, D., Dehaene, S. & Zorzi, M. (2010). Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. *Cognition*, *116*, 33–41. doi:10.1016/j.cognition.2010.03.012

Price, G. R., Holloway, I., Räsänen, P., Vesterinen, M., & Ansari, D. (2007). Impaired parietal magnitude processing in developmental dyscalculia. *Current Biology*, *17*, R1042–R1043. doi:10.1016/j.cub.2007.10.013

Rousselle, L., & Noël, M. P. (2007). Basic numerical skills in children with mathematics learning disabilities: A comparison of symbolic vs non-symbolic number magnitude processing. *Cognition*, *102*, 361–395. doi:10.1016/j.cognition.2006.01.005

Rubinsten, O., & Henik, A. (2009). Developmental dyscalculia: Heterogeneity might not mean different mechanisms. *Trends in Cognitive Sciences*, *13*, 92–99. doi:10.1016/j.tics.2008.11.002
Rubinsten, O., & Sury, D. (2011). Processing ordinality and quantity: The case of developmental dyscalculia. *PLoS ONE*, *6*, e24079. doi:10.1371/journal.pone.0024079
Sasanguie, D., Lyons, I. M., De Smedt, B., & Reynvoet, B. (2017). Unpacking symbolic number comparison and its relation with arithmetic in adults. *Cognition*, *165*, 26–38. doi:10.1016/j.cognition.2017.04.007
Sattler, J. M., & Dumont, R. (2004). *Assessment of children: WISC-IV and WPPSI-III supplement*. San Diego, California: Jerome M. Sattler, Publisher.
Siegler, R. S., & Opfer, J. E. (2003). The development of numerical estimation evidence for multiple representations of numerical quantity. *Psychological Science*, *14*, 237–250. doi:10.1111/1467-9280.02438
St Clair-Thompson, H. L., & Gathercole, S. E. (2006). Executive functions and achievements in school: Shifting, updating, inhibition, and working memory. The quarterly journal of experimental psychology, 59(4),745–759. DOI: 10.1080/17470210500162854.
Skagerlund, K., & Träff, U. (2014). Development of magnitude processing in children with developmental dyscalculia: Space, time, and number. *Frontiers in Psychology*, *5*, 675. doi:10.3389/fpsyg.2014.00675
Skagerlund, K., & Träff, U. (2016). Number processing and heterogeneity of developmental dyscalculia: Subtypes with different cognitive profiles and deficits. Journal of Learning Disabilities, 49, 36–50.DOI: 10.1177/0022219414522707
Soltész, F., Szűcs, D., Dékány, J., Márkus, A., & Csépe, V. (2007). A combined event-related potential and neuropsychological investigation of developmental dyscalculia. Neuroscience Letters, 417, 181–186. DOI: 10.1016/j.neulet.2007.02.067
Swanson, H. L. (2011). Working memory, attention, and mathematical problem solving: A longitudinal study of elementary school children. *Journal of Educational Psychology*, *103*, 821–837. doi:10.1037/a0025114
Szűcs, D., Devine, A., Soltész, F., Nobes, A., & Gabriel, F. (2013). Developmental dyscalculia is related to visuo-spatial memory and inhibition impairment. *Cortex*, *49*, 2674–2688. doi:10.1016/j.cortex.2013.06.007
Szűcs, D., Nobes, A., Devine, A., Gabriel, F., & Gebuis, T. (2013). Visual stimulus parameters seriously compromise the measurement of approximate number system acuity and comparative effects between adults and children. *Frontiers in Psychology.*, *4:444*. doi:10.3389/fpsyg.2013.00444
Tabachnick, B. G., & Fidell, L. S. (2007). *Using multivariate statistics*. Allyn & Bacon/Pearson Education, Boston, Massachusetts.
Turconi, E., Campbell, J. I. D., & Seron, X. (2006). Numerical order and quantity processing in number comparison. *Cognition*, *98*, 273–285. doi:10.1016/j.cognition.2004.12.002
Vicario, C. M., Rappo, G., Pepi, A., Pavan, A., & Martino, D. (2012). Temporal abnormalities in children with developmental dyscalculia. *Developmental Neuropsychology*, *37*, 636–652. doi:10.1080/87565641.2012.702827
Vincent, D., & Crumpler, M. (2007). *Hodder group reading tests 1–3 (II)*. London, UK: Hodder Education.
Vogel, S. E., Remark, A., & Ansari, D. (2015). Differential processing of symbolic numerical magnitude and order in first-grade children. *Journal of Experimental Child Psychology*, *129*, 26–39. doi:10.1016/j.jecp.2014.07.010
von Aster, M. G., & Shalev, R. S. (2007). Number development and developmental dyscalculia. *Developmental Medicine and Child Neurology*, *49*, 868–873. doi:10.1111/j.1469-8749.2007.00868.x
Vos, H., Sasanguie, D., Gevers, W., & Reynvoet, B. (2017). The role of general and number-specific order processing in adults' arithmetic performance. *Journal of Cognitive Psychology*, *29*, 469–482. doi:10.1080/20445911.2017.1282490
Wechsler, D. (2003). *Wechsler intelligence scale for children* (4th ed.). Oxford, England: Psychological Corp.
Williams, J. (2005). *Mathematics assessment for learning and teaching*. London, UK: Hodder Education.

Appendix: Parental Report of Everyday Ordering Ability

Please circle the number which you feel best applies to your child for each question.

My son/daughter:
Can easily adjust to changes in routine.
(1 = very much disagree; 7 = very much agree)
1—-2—-3—-4—-5—-6—-7

Understands how the calendar works.
(1 = very much disagree; 7 = very much agree)
1—-2—-3—-4—-5—-6—-7

Can easily recall the order in which past events happened.
(1 = very much disagree; 7 = very much agree)
1—-2—-3—-4—-5—-6—-7

Is able to plan a sequence of activities independently.

(1 = very much disagree; 7 = very much agree)
1—-2—-3—-4—-5—-6—-7

Finds it easy to learn new activities which involve a sequence of actions that have to be performed in a particular order (e.g., when learning to play computer or board games).
(1 = very much disagree; 7 = very much agree)
1—-2—-3—-4—-5—-6—-7

Would find it easy to remember a phone number.
(1 = very much disagree; 7 = very much agree)
1—-2—-3—-4—-5—-6—-7

Can organise their own time when doing certain tasks (e.g., can decide in what order to do different pieces of homework).
(1 = very much disagree; 7 = very much agree)
1—-2—-3—-4—-5—-6—-7

The Stability of Individual Differences in Basic Mathematics-Related Skills in Young Children at the Start of Formal Education

Patrick A. O'Connor[1], Kinga Morsanyi[1], and Teresa McCormack[1]

ABSTRACT— The current study investigated the development of children's performance on tasks that have been suggested to underlie early mathematics skills, including measures of cardinality, ordinality, and intelligence. Eighty-seven children were tested in their first (T1) and second (T2) school year (at ages 5 and 6). Children's performance on all tasks demonstrated good reliability and significantly improved with age. Correlational analyses revealed that performance on some mathematics-related tasks were nonsignificantly correlated between T1 and T2 (number line and number comparison), showing that these skills are relatively unstable. Detailed analyses also indicated that the way children solve these tasks show qualitative changes over time. By contrast, children's performance on measures of intelligence and nonnumerical ordering abilities were strongly correlated between T1 and T2. Additionally, ordering skills also showed moderate to strong correlations with counting procedures both cross-sectionally and longitudinally. These results suggest that, initially, mathematics skills strongly rely on nonmathematical abilities.

Much research into important early predictors of mathematical development have been concerned with investigating the extent to which cardinal skills (both symbolic and nonsymbolic) are involved in the acquisition of symbolic number knowledge. However, recent evidence has suggested that ordinality, a key property of numbers along with cardinality (Gelman & Gallistel, 1978), may also play an important role in early number development, as may other general factors, such as intelligence (e.g., Roth et al., 2015). Studies often administer a set of these predictors together, in order to establish which measures are most closely related to formal mathematics skills. Such results are then interpreted in a causal way, by assuming that tasks that most strongly predict mathematics skills form the foundation of those skills. Nevertheless, these studies typically do not investigate and take into account the stability of individual differences in those predictors over time. Indeed, it is important to distinguish between tasks that are merely correlated with mathematics skills, but do not reflect stable individual differences, as opposed to skills that show intraindividual stability, and might form the foundations of learning mathematics, as this knowledge could inform theories regarding the typical and atypical development of mathematics skills, as well as intervention efforts. Thus, the aim of the present study was to investigate the stability of several numerical and nonnumerical predictors of early mathematical success, in order to identify a set of skills that are already in place at the start of formal education, and could support the development of early mathematics competence. In the following sections, we describe the tasks that we considered in our study.

Previous research has proposed the existence of an innate, evolutionarily ancient system for processing cardinality, which is not dependent on language skills and

[1]School of Psychology, Queen's University Belfast

Address correspondence to Patrick A. O'Connor, School of Psychology, Queen's University Belfast, David Keir Building, Malone Road, Belfast, BT9 5AG, Northern Ireland; e-mail: poconnor08@qub.ac.uk

is not unique to humans, referred to as the "approximate number system" (ANS; Piazza et al., 2010). Evidence from meta-analyses appear to support the role of the ANS in early numerical development (Chen & Li, 2014; Fazio, Bailey, Thompson, & Siegler, 2014; Schneider et al., 2017). Many studies have used the Dot comparison task as a measure of the ANS; however, there have been questions raised about the reliability and validity of this measure (e.g., Gilmore et al., 2013; Inglis & Gilmore, 2013, 2014; Maloney, Risko, Preston, Ansari, & Fugelsang, 2010; Price, Palmer, Battista, & Ansari, 2012). There is evidence to suggest that a nonsymbolic addition task (e.g., Barth, La Mont, Lipton, & Spelke, 2005) may be a more viable alternative measure of the ANS. Several studies (Barth, Beckmann, & Spelke, 2008; Barth et al., 2005; Li et al., 2017) have found that young children can perform above chance on this task and show similar patterns of responding as adults. Additionally, this task appears to measure a similar underlying construct as the Dot comparison task (Gilmore, Attridge, De Smedt, & Inglis, 2014). Performance on the nonsymbolic addition task has also been linked to mathematical achievement in developmental studies (Gilmore, McCarthy, & Spelke, 2010; Wong, Ho, & Tang, 2016).

Whereas much research has focused on nonsymbolic magnitude skills, symbolic magnitude skills (typically indexed by the number comparison task) appear to be more strongly related to mathematics. This is particularly evident in studies involving children aged 6 and over (De Smedt, Noël, Gilmore, & Ansari, 2013; Fazio et al., 2014; Schneider et al., 2017). This suggests that these skills may exert more of an influence after children have had some experience of formal mathematics learning at school.

There is now considerable evidence in support of a link between order-processing skills and mathematical abilities. Although it appears that numerical ordering skills become particularly important from around the age of 6 or 7 (Attout & Majerus, 2018; Lyons, Price, Vaessen, Blomert, & Ansari, 2014; Sasanguie & Vos, 2018), there is also now emerging evidence in support of a role of nonnumerical ordering in mathematical development in the case of younger children (Attout, Noël, & Majerus, 2014; Morsanyi, van Bers, O'Connor, & McCormack, 2018; O'Connor, Morsanyi, & McCormack, 2018). Nonnumerical order processing measures can be broadly divided into two categories: those involving the retrieval of a familiar sequence from long-term memory, such as the order of familiar daily events, familiar everyday sequences, the months of the year, or letters (Morsanyi, O'Mahony, & McCormack, 2017; O'Connor et al., 2018; Sasanguie, De Smedt, & Reynvoet, 2017; Vos, Sasanguie, Gevers, & Reynvoet, 2017), and those involving the retrieval of a novel, arbitrary sequence from short-term memory (order working memory [WM] task; Attout & Majerus, 2015, 2018; Attout et al., 2014). O'Connor et al. (2018) found that both numerical and nonnumerical ordering measures were related to early mathematical achievement in 4–5-year-old children. However, the ordering of familiar sequences was the strongest predictor of children's mathematics achievement at the end of their first year of school, and also longitudinally predicted mathematics achievement at the end of their second year, after controlling for the effect of several numerical and nonnumerical tasks. Order WM performance also correlated with mathematics achievement but did not explain additional variance after taking into account the effect of the order-processing measures involving the retrieval of familiar content.

Performance on number line estimation tasks have been proposed to reflect representations of number along a mental number line (e.g., Bonato, Zorzi, & Umiltà, 2012; Kaufmann, Vogel, Starke, Kremser, & Schocke, 2009; Link, Huber, Nuerk, & Moeller, 2014; Moyer & Landauer, 1967). Furthermore, number line performance has been linked to early numerical development, even in very young children (e.g., Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Siegler & Booth, 2004; Siegler & Opfer, 2003), suggesting that estimation skills may be important to early mathematics learning. However, Schneider et al. (2018) found that effect sizes, regarding the relation between number line estimation and mathematics achievement, increased with age (.30 for children below 6; .44 for 6–9-year-olds; and .49 for 9–14-year-olds). This finding suggests a codevelopment of number line estimation and formal mathematical skills with time.

Finally, there is evidence that intelligence is strongly related to academic achievement (e.g., Morsanyi, van Bers, McCormack, & McGourty, 2018), and also to other socioeconomically relevant outcomes, such as future employment and income (Deary, Strand, Smith, & Fernandes, 2007; Roth et al., 2015; Strenze, 2007). This suggests not only that verbal and nonverbal intelligence are important to mathematical achievement during the school years, but are also related to children's future prospects after they have left school.

As mentioned above, while many studies have tried to identify which early predictors are important to numerical development, there is a relative lack of understanding as to the stability of these skills over time. Nevertheless, there are a few longitudinal studies that reported data regarding the stability of performance on some basic numerical tasks (e.g., Attout et al., 2014; Reeve, Reynolds, Humberstone, & Butterworth, 2012; Xenidou-Dervou, Molenaar, Ansari, van der Schoot, & van Lieshout, 2017), the findings of which are summarized in Table 1. These results suggest that although performance on these tasks shows some consistency over time during the first school years, the strength of the correlations is generally weak to moderate, and sometimes even nonsignificant.

Table 1
Table Showing the Results of Three Longitudinal Studies Regarding the Stability of Cardinal and Ordinal Measures

	Between 6 and 7 years of age	*Between 7 and 8 years of age*
Attout et al. (2014)		
Order WM	.58**	.30*
Number ordering	.27*	.36**
Number comparison	.30*	−.05
Reeve et al. (2012)		
Dot enumeration	.46**	–
Number comparison	.16	.52**
Xenidou-Dervou et al. (2017)		
Dot comparison	.21**	.28**
Number comparison	.21**	.25**

Note. WM = working memory.

The Current Study

The aim of the current study was to investigate the development of ordinal, cardinal, and intelligence measures between children's first (T1) and second (T2) year of primary school (i.e., between the ages of 4 and 6) in a group of pupils from Northern Ireland, a country which has one of the youngest school starting ages in Europe (Eurydice at NFER, 2012); children in Northern Ireland begin primary school on the first September after their fourth birthday. We expected that each of these skills would show significant improvements between the first 2 years of school. Additionally, we aimed to assess the stability of individual differences in these skills, by analyzing correlations between performance on each task across the two school years. Strong correlations between task performance at each time point would show evidence of the stability of the skills that the tasks measure, while weak or nonsignificant correlations would suggest that the underlying processes and strategies are still developing.

We also investigated the relations between each task and counting skills (i.e., counting forward and backward from different starting points), both cross-sectionally and longitudinally. We considered the counting task an indicator of familiarity with the number system, as well as the flexibility with which children could use numbers. These skills are essential for the development of arithmetic abilities (e.g., Geary, Brown, & Samaranayake, 1991; Lemaire & Siegler, 1995), and, thus are very important for the development of formal mathematics skills. Tasks that show strong relations with counting skills at each time point can be considered diagnostic of mathematics skills. Nevertheless, we expected that the way children perform some of these tasks might change considerably during the first school years (e.g., because children automatize some procedures or develop new strategies). Only tasks that show stability over time can be considered as potential candidates for skills that might form the foundations of mathematics abilities. Indeed, if performance on a task is not strongly related to performance on the same task at a later time point, it could not be considered as a good indicator of individual differences in a basic skill.

Where it was possible, we also performed detailed analyzes of some within-task variables, in order to investigate how the effect of these variables on children's performance changed between T1 and T2. This could help in explaining the findings regarding the stability of individual differences on each task.

METHOD

Participants

Eighty-seven children participated in the study (43 females, mean age at T1 = 4 years 11 months; *SD* = 3.73 months; mean age at T2 = 6 years 2 months, *SD* = 3.44 months).[1] Due to the demographics of the population in Northern Ireland, the vast majority of children were of Caucasian origin. Children's level of socioeconomic deprivation was determined using the Northern Ireland multiple deprivation measure (Northern Ireland Statistics and Research Agency, 2010). This measure assigns a deprivation score to each electoral ward in Northern Ireland based on seven indices (income deprivation; employment deprivation; health deprivation and disability; education, skills, and training deprivation; proximity to services; living environment; and crime and disorder). A higher score indicates a higher level of deprivation for the area. The scores can be interpreted as percentiles (e.g., a score of 10 means that the area is less deprived than 90% of all postcode-based areas within Northern Ireland). In the current sample, deprivation scores ranged from 1.85 to 68.57 (median deprivation score = 11.00). Based on children's postcodes, most children came from areas with very low levels of socioeconomic deprivation, reflecting that the majority of the sample came from areas of higher socioeconomic status, although deprivation indices ranged from low to medium. One child did not provide a postcode, so a deprivation score could not be calculated for that child.

Materials

Intelligence Quotient

Verbal and nonverbal intelligence was measured using the vocabulary and block design subtests of the Wechsler Preschool and Primary Scale of Intelligence—Third UK Edition (WPPSI-III UK; Wechsler, 2003). Children's estimated full-scale intelligence quotient (IQ) scores were computed following the method outlined in Sattler and Dumont (2004) and were found to be within the normal range at both time points (mean T1 IQ score = 95.92, *SD* = 13.51; mean T2 IQ score = 101.80, *SD* = 12.45).

Order WM Task
This was based on a similar measure developed by Majerus, Poncelet, Greffe, and Van der Linden (2006). This task measures children's ability to retain and manipulate serial order information by measuring their ability to recreate the correct sequence of a list of animal names that were presented to them through a set of earphones, using cards depicting the animals. The length of item sequences ranged from two to seven, with four items at each level. Split-half reliability estimates, using the Spearman-Brown formula, indicated good reliability (T1: $r = .93$; T2: $r = .95$).

Daily Events Task
This computerized task was based on Friedman's (1977, 1990) temporal ordering task. Children were shown three daily events, out of a set of six (half of the trials were in canonical order, from left to right; half were in a mixed order) and judged whether the order was correct or not, from right to left, by pressing either a tick or a cross on the touchscreen monitor. Since each trial was presented twice (with a total of 24 trials), a split-half reliability was calculated using the Spearman-Brown coefficient, which was found to be adequate (T1: $r = .57$; T2: $r = 76.$).

Counting
In this task, children were first asked to count to 50 (T1) or 100 (T2) twice. Additionally, children had to count forward and backward (three trials for each direction) from different starting points. Children could correct themselves once during any trial and were stopped once they had correctly recited the next three numbers in the sequence. A score of 1 was given for each trial in which children correctly recited the next three numbers in the sequence. A total counting score was calculated by adding z scores for all three counting measures (counting until 50 or 100, counting forward from different starting positions and counting backward from different starting positions). The reliability estimate for the task was good (T1 Cronbach's alpha = .77; T2 Cronbach's alpha = .75).

Nonsymbolic Addition
This computerized task was based on the one used by Gilmore et al. (2010), in which children had to approximately add two arrays of dots together (sum array) and compare the sum of these to a comparison array of dots. The numerical ratio of the sum and comparison arrays was manipulated across the 24 trials (1:2, 3:5, and 2:3), with eight trials per ratio. The number of dots for both arrays varied from 6 to 45, with 6 being the lowest number of dots as this reduced the possibility that children could subitize the number of dots presented. Perceptual variables (dot size, density, and array size) were also varied, so that they correlated with numerosity on half the trials (congruent trials) and were uncorrelated on the other half of the trials (incongruent trials), reducing the possibility that children may have used perceptual information as a cue when judging which array was the most numerous. In the task, children had to press one of two buttons on the touchscreen to indicate which character they thought had the most marbles. They first completed four practice trials, with feedback given on their performance. Children were given a score of 1 if they correctly judged which character had the most marbles. Reliability for this task was low, but acceptable (T1 Cronbach's alpha = .50; T2 Cronbach's alpha = .63), and one-sample t tests confirmed that children performed above chance at each ratio.

Number Comparison
In a computerized task, children were presented with a target number (between 1 and 4 or 6 and 9) and were asked to press one of two buttons (either a large square or a small square) to indicate whether they thought that the number on the screen was larger or smaller than 5. Children were presented with four practice trials before completing the task. Task performance showed high reliability (T1 Cronbach's alpha = .88; T2 Cronbach's alpha = .84).

Number Line Task
This was a computerized task in which children had to indicate the position of numbers along a 1–10 and a 1–20 number line, both of which were of equal length (1,000 pixels). There were two practice trials and six experimental trials for each scale. Children's error for each individual trial was calculated as the distance in pixels between children's estimated position and the actual position of the target number. The average of children's errors across both 1–10 and 1–20 scales was used as the overall measure of estimation error for the task. The task showed adequate reliability (T1 Cronbach's alpha = .70; T2 Cronbach's alpha = .71).

Procedure
The study received ethical approval from the university department's ethics committee. Parents gave consent for their child to take part in the study. In Session 1, all children completed the number comparison task, the order WM task and finally, the nonsymbolic addition task. In Session 2, children completed the daily events task, followed by the WPPSI-III subtests, counting task, and then finally the number line task. In year 1, there was a 3-month gap between session 1 and session 2, while in year 2, there was a 2-month gap between session 1 and session 2. The computer-based tasks were designed using E-Prime Version

Table 2
Descriptive Statistics for All Measures at T1 and T2 Along With the Results of Paired Sample *t* Tests Comparing T1 and T2 Performance

Measure	*T1*			*T2*			t	d
	Min.	*Max.*	*M* (SD)	*Min.*	*Max.*	*M* (SD)		
Vocabulary (raw score)	7	32	16.08 (6.76)	7	37	22.62 (5.90)	10.45**	1.03
Block design (raw score)	16	32	24.20 (3.50)	24	40	29.45 (3.94)	12.01**	1.41
Order WM	1	16	9.52 (4.54)	1	19	10.89 (4.37)	3.36**	.31
Daily events accuracy	.38	1	.65 (.13)	.46	1	.76 (.13)	8.10**	.85
Nonsymbolic addition	.30	.88	.56 (.11)	.33	.96	.64 (.13)	5.66**	.66
Number comparison accuracy	.40	1	.71 (.19)	.55	1	.95 (.08)	11.76**	1.65
Number line task (mean scaled error)	64	453	191.52 (74.90)	41	325	126.94 (56.00)	6.63**	.98

Note. WM = working memory.
*$p < .05$. **$p < .01$.

2.0. These tasks were presented on a touch screen, connected to a laptop. All tasks were administered individually. For all computer-based tasks, accuracy and reaction times were recorded, but in the following we only report the results regarding accuracy.

RESULTS

The descriptive statistics for children's performance on tasks at T1 and T2, as well as the results of repeated measures *t* tests and the effect sizes of differences across the two time points, are presented in Table 2. The *t* tests indicated that children's task accuracy improved significantly on all tasks, when compared to their performance on the same tasks at T1. The effect size of these developmental changes was large for all tasks, with the exception of the order WM task, where the effect size was medium.

Children's performance on the counting task also showed large improvements over this period. At T1, the median number that children were able to count up to (out of a maximum of 50) was 39, while at T2, the median number that children were able to count up to (out of 100) was 100, showing that by the second year of school, most children were familiar with the number system up to 100. Additionally, children made significantly fewer mistakes at T2 when they were counting forward and backward from different starting points (T1 accuracy: 76%; T2 accuracy: 92%), although they were given larger starting numbers at T2.

In order to investigate the stability of individual differences on these tasks, correlation analyses were conducted between performance on each task at T1 and T2. A bootstrap procedure (using 10,000 samples) was also applied to obtain 95% confidence intervals for the correlation coefficients. Figure 1 shows that performance on the majority of measures at T1 showed significant bootstrap correlations with performance at T2. The only exceptions were number comparison: $r = .20$, 95% confidence interval (CI) (−.01, .34); and number line performance: $r = -.01$, 95% CI (−.25, .25).

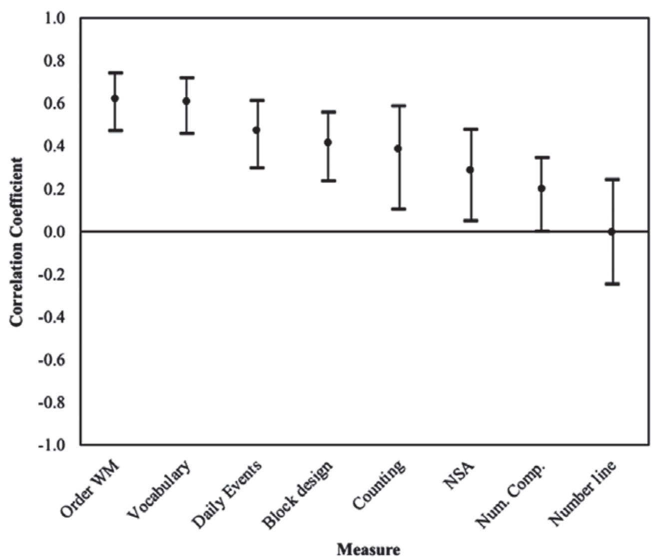

Fig. 1. Bootstrap correlation analysis for task accuracy between T1 and T2.

The 95% confidence intervals for the order WM task: $r = .62$, 95% CI (.47, .74); vocabulary: $r = .61$, 95% CI (.46, .72), and daily events task: $r = .48$, 95% CI (.30, .61), did not overlap with the 95% confidence intervals for the number line task, which suggests that the magnitude of correlations for the former three tasks was significantly greater than the correlation for number line performance. The 95% confidence intervals for the order WM and vocabulary measures also did not overlap with the confidence intervals for number comparison, again indicating that the correlations between T1 and T2 task performance for order WM and vocabulary were significantly greater than the correlation between the two time points for the number comparison task. That is, there were significant variations in the stability of individual differences on these tasks, with performance on the number line and number comparison tasks appearing to be the least stable, and order WM and vocabulary performance being the

Table 3
Correlations Between Counting Skills and All Measures at T1 and T2

T1 task performance	*Counting T1*	*Counting T2*	*T2 task performance*	*Counting T2*
Vocabulary	.27**	.10	Vocabulary	.27**
Block design	.13	.24*	Block design	.26**
Order WM	.54**	.43**	Order WM	.37**
Daily events	.34**	.36**	Daily events	.25**
Nonsymbolic addition	.02	.23*	Nonsymbolic addition	.22*
Number comparison	.29**	.33**	Number comparison	.38**
Number line	.06	−.003	Number line	.11

Note. WM = working memory.
*$p < .05$. **$p < .01$.

most stable. The 95% confidence intervals for block design: $r = .41$, 95% CI (.24, .56); counting: $r = .39$, 95% CI (.10, .60): and nonsymbolic addition tasks: $r = .29$, 95% CI (.05, .48), overlapped with the 95% confidence intervals for the number line and number comparison tasks, which suggests that the magnitude of correlations for the former three tasks was not significantly greater than the correlation for number line and number comparison performance. Overall, these results suggested that the way children performed most numerical tasks showed important changes as a result of formal education, whereas individual differences on nonnumerical tasks showed moderate to high stability.

A correlation analysis was conducted to investigate the relationships between performance on each task and counting ability at both time points. As shown in Table 3, order WM, daily events, and number comparison performance showed the most consistent correlations with counting ability, which was present for both cross-sectional and longitudinal analyses. Regarding verbal and nonverbal intelligence, vocabulary skills related to counting ability at both time points, but not longitudinally, whereas nonverbal intelligence appeared to play a more important role at T2. For nonsymbolic addition, the pattern was similar to nonverbal intelligence, as the task was significantly related to counting only at T2. Number line performance was unrelated to counting ability at both time points.

In order to better investigate the developmental changes that happened over the first school years, we conducted further analyses where we investigated the effects of various within-task variables (e.g., distance effects, ratio effects).

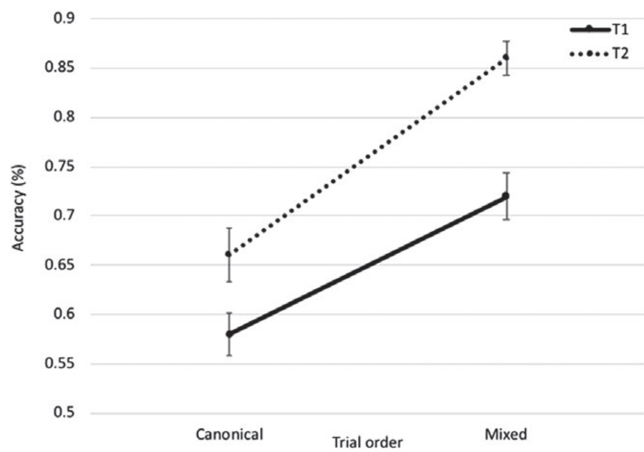

Fig. 2. Graph plotting accuracy on the daily events task by time and trial type (error bars represent the standard error of the mean). Dotted line—Daily events accuracy at T1. Solid line—Daily events accuracy at T2.

Daily Events

A 2 × 2 mixed analysis of variance (ANOVA) was carried out to determine the effect of time (T1 and T2) and trial order (canonical and mixed) on daily events task accuracy (Figure 2). The analysis revealed a significant main effect of trial order, $F(1, 86) = 37.48$, $p < .001$, $\eta_p^2 = .30$. Children performed significantly better on mixed-order trials (mean = 79%), compared to canonical order trials (mean = 62%). There was also a main effect of time, $F(1, 86) = 65.20$, $p < .001$, $\eta_p^2 = .43$. Children performed significantly better on the task at T2 (mean = 76%) than at T1 (mean = 65%). However, there was no interaction between time and trial order ($p = .233$).

Number Comparison

A 2 × 4 mixed ANOVA was carried out to determine the effect of time (T1 and T2) and numerical distance between the two to-be-compared numbers (distances of 1, 2, 3, or 4) on number comparison accuracy. The analysis revealed a significant main effect of time, $F(1, 87) = 133.12$, $p < .001$, $\eta_p^2 = .61$. Children performed significantly better on the task at T2 (mean = 95%), compared to T1 (mean = 72%). There was also a main effect of numerical distance, $F(2.78, 241.51) = 25.93$, $p < .001$, $\eta_p^2 = .23$. Bonferroni-corrected pairwise comparisons revealed that children performed significantly worse on numerical distance 1 trials (mean = 77%), compared to performance on

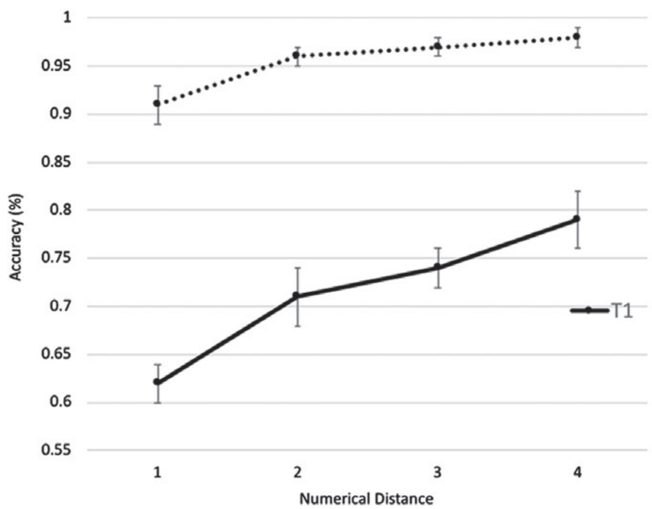

Fig. 3. Graph plotting accuracy on the number comparison task by numerical distance and time (error bars represent the standard error of the mean). Dotted line—Number comparison accuracy at T1. Solid line—Number comparison accuracy at T2.

distance 2 (mean = 84%; $p < .001$); distance 3 (mean = 85%; $p < .001$); and distance 4 trials (mean = 88%; $p < .001$). The analysis also revealed a significant time by distance interaction, $F(2.66, 231.66) = 3.66$, $p = .017$, $\eta_p^2 = .181$, which showed that the distance effect at T2 was significantly reduced compared to T1 (Figure 3).

Nonsymbolic Addition

A 2×2×3 mixed ANOVA was carried out to determine the effect of time (T1 and T2), congruency (congruent and incongruent trials; congruent trials are those in which the perceptual features of the array correlated with numerosity), and numerical ratio (1:2, 3:5, and 2:3) on nonsymbolic addition accuracy (see Figure 4). The analysis revealed a significant main effect of time, $F(1, 87) = 31.31$, $p < .001$, $\eta_p^2 = .27$. Children performed significantly better on the task at T2 (mean = 65%), compared to T1 (mean = 56%).

There was also a main effect of congruency, $F(1, 87) = 375.15$, $p < .001$, $\eta_p^2 = .812$. Children tended to perform significantly better on congruent trials (mean = 87%), compared to incongruent trials (mean = 34%). There was also a main effect of numerical ratio, $F(2, 174) = 6.39$, $p = .002$, $\eta_p^2 = .07$. Bonferroni-corrected pairwise comparisons revealed that children's performance on 1:2 trials (mean = 63%) was significantly better compared to performance on 2:3 trials (mean = 58%, $p = .003$).

The analysis also revealed a significant time by congruency interaction, $F(1, 87) = 6.70$, $p = .011$, $\eta_p^2 = .07$, which showed that children's performance significantly improved on the incongruent trials across the two time points, but their performance remained stable on the congruent trials (see Figure 3). Finally, there was also a significant congruency by ratio interaction, $F(2, 174) = 4.14$, $p = .018$, $\eta_p^2 = .045$. This reflected a significant ratio effect for incongruent trials only.

Number Line

A 2×2 mixed ANOVA was carried out to examine the effect of time (T1 and T2) and numerical scale (1–10 and 1–20) on number line estimation accuracy. The analysis revealed a significant main effect of time, $F(1, 86) = 43.96$, $p < .001$, $\eta_p^2 = .34$. Children's estimations were closer to the target numbers at T2 (mean = 126.94 pixels), compared to T1 (mean = 193.61 pixels). There was also a main effect of scale, $F(1, 86) = 30.66$, $p < .001$, $\eta_p^2 = .26$. Children's estimations were closer to the target numbers on the 1–20 scale (mean = 137.65 pixels), compared to the 1–10 scale (mean = 182.90).

There was a significant time by scale interaction, $F(1, 86) = 7.41$, $p = .008$, $\eta_p^2 = .08$, which showed that the improvement in performance over time was much greater on the 1–20 number line than on the 1–10 number line (Figure 5).

DISCUSSION

The current study investigated young children's performance on a series of numerical and nonnumerical tasks that have been previously identified as important predictors of early formal mathematics skills in the first years of primary school. Although children in Northern Ireland start primary school at an unusually young age, they were able to perform all of these tasks, and their performance could be measured with acceptable to high reliability. A comparison of children's performance on these tasks between the first and second school years also showed that children's skills on all tasks greatly improved (with a more modest improvement on the order WM task).

When identifying tasks that form the basis of early competence, and can be indicative of children's later mathematics ability, the focus should be on tasks that are not only related to mathematics skills, but also show stable individual differences over time. We can assume that if performance on a task does not show continuity over time within an individual, the task is not indexing a basic skill. Rather, this pattern indicates that children are in the process of developing new strategies and skills that are relevant for performance on the task. By contrast, tasks that show stability over time *and* are also diagnostic of mathematics skills can be considered more reliable indicators of individual differences in some relevant skills. This distinction is important, because it is often assumed in the mathematics cognition literature that numerical skills originate in some basic abilities that are present from early development.

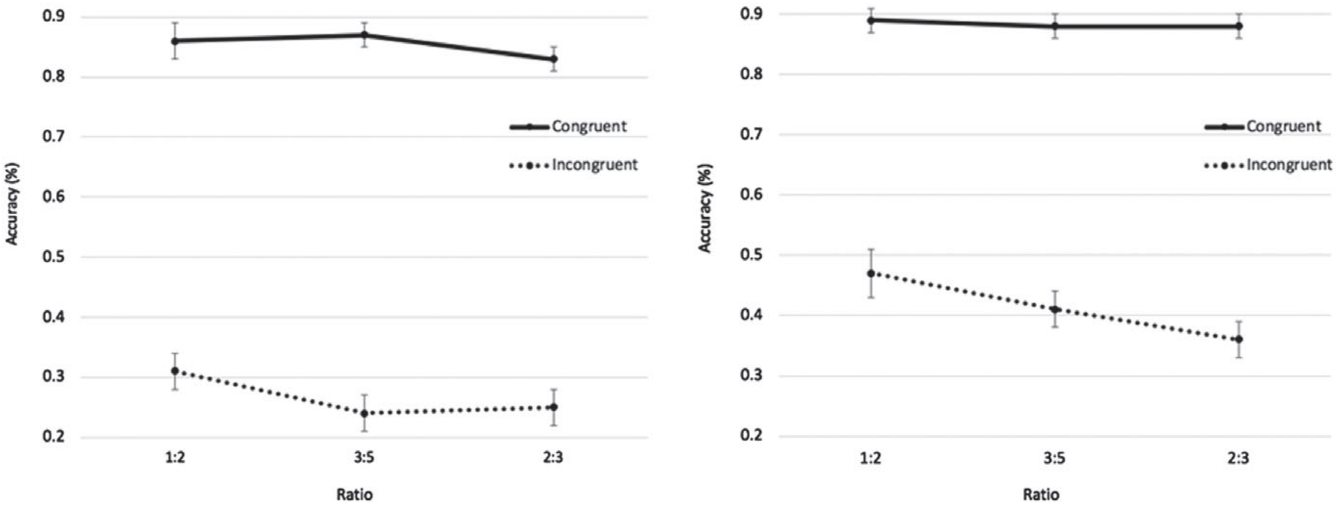

Fig. 4. Graph plotting accuracy on the nonsymbolic addition task by ratio and congruency at T1 (left) and at T2 (right) (error bars represent the standard error of the mean). Dotted line—Nonsymbolic addition accuracy at T1. Solid line—Nonsymbolic addition accuracy at T2.

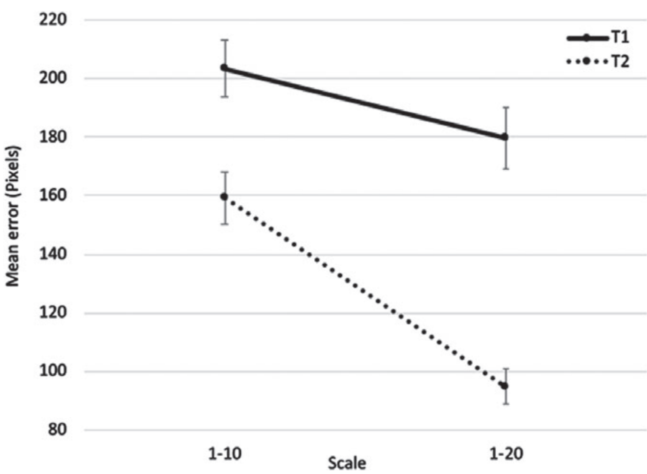

Fig. 5. Graph plotting mean estimation error on the number line task by time and scale (error bars represent the standard error of the mean). Dotted line—Number line mean estimation error at T1. Solid line—Number line mean estimation error at T2.

The results of the current study suggest that, among the tasks which have been previously identified as important predictors of early formal mathematics skills, individual differences in the order-processing and intelligence measures remained highly consistent across the first 2 years of primary school. Counting skills and nonsymbolic addition accuracy showed moderate consistency over time, whereas performance on the number comparison task and the number line task showed little consistency.

Regarding the predictive value of these tasks, three tasks showed consistent relationships with counting ability: order WM, the daily events task, and number comparison. Based on the results regarding the stability of individual differences on these tasks, we can argue that, whereas the two ordering tasks are reliable indicators of individual differences in some early-developing skills related to counting, number comparison performance can be considered merely diagnostic of the current developmental stage of some relevant skills, as it shows little consistency over time. Indeed, our results suggest that there are important changes in how children perform this task. In particular, children's responses at T2 were less affected by the numerical distance between the numbers that they had to compare, relative to their performance at T1.

Other tasks that were less stable over time included the nonsymbolic addition and the number line tasks. On the nonsymbolic addition task, children's performance showed particular improvements in the case of incongruent trials, indicating that they were more able to focus on the number of items presented instead of the perceptual properties of the display (i.e., overall size and surface area), although, as a group, children continued to perform poorly on incongruent trials even at T2. In the case of the number line task, children showed particular improvement in the 1–20 number line, suggesting that they became increasingly familiar with larger numbers.

Overall, these findings are supportive of an important role for nonnumerical ordering skills in the early development of formal mathematics abilities during the first years of primary school, including the ordering of both familiar and novel sequences (e.g., Attout et al., 2014; O'Connor et al., 2018). The results of the current study also extend earlier findings regarding the importance of these skills by showing evidence of the stability of children's temporal ordering skills, as well as their order WM during the early years of primary school (see also Attout et al., 2014).

Although nonsymbolic numerical skills have been cited as being important in early numerical development (e.g., Chen & Li, 2014; Fazio et al., 2014; Schneider et al., 2017), the results of the current study fail to support this assertion, therefore calling into question the claim that the ANS plays a pivotal role in early symbolic number knowledge acquisition (e.g., Chen & Li, 2014; Halberda, Mazzocco, & Feigenson, 2008; Holloway & Ansari, 2009; Piazza et al., 2010; Wong et al., 2016). At the same time, the current results are in line with earlier findings that young children struggle to disregard the perceptual properties of nonsymbolic displays (Rousselle, Palmers, & Noël, 2004; Soltész, Szűcs, & Szűcs, 2010), —although their performance on incongruent trials (in which perceptual properties have to be inhibited in order to respond correctly) improved between T1 and T2, they were still performing poorly on these trials.

It could be argued that the counting task only assessed a small facet of early formal mathematical skills, and because of the forward and backward counting subtasks, it is unsurprising that performance on this task was related to ordering abilities. Nevertheless, O'Connor et al. (2018) found, using data from the same data set as was used in the current study, that performance on the ordering tasks strongly related to formal mathematics skills (as measured by comprehensive, curriculum-based tests). This result was found both cross-sectionally and longitudinally, and these relations were also somewhat stronger than the correlations between number comparison and formal mathematics skills, which is similar to the current results.

It is important to note that our results do not question the importance of magnitude processing skills in mathematics development. Indeed, these skills appear to codevelop with other formal mathematics skills, and might be highly diagnostic of children's mathematics competence. Nevertheless, these skills go through some qualitative changes in the first years of school, and show little intraindividual stability, which makes it unlikely that they could form the basis of the development of other mathematical skills. That is, it seems unlikely that these skills could play such a role until performance on these tasks reaches a certain level of stability.

The current findings regarding the low intertemporal stability of nonsymbolic magnitude skills are in line with Inglis and Gilmore (2014) who found moderate correlations (around .5) between children's performance on a nonsymbolic magnitude comparison task and their performance on the same task 1 week later. Thus, even within a short time period, children's performance on the task fluctuated considerably. Apart from more general issues with the reliability of nonsymbolic magnitude processing tasks (Gilmore et al., 2013; Inglis & Gilmore, 2013, 2014; Maloney et al., 2010; Price et al., 2012), it has been suggested that performance on these tasks in the case of young children depends on some domain-general skills, such as inhibition (Fuhs & McNeil, 2013) and working memory (Xenidou-Dervou, De Smedt, van der Schoot, & van Lieshout, 2013). These findings are in line with our proposal that children's performance might reflect a variety of skills and strategies rather than a single underlying ability. These skills and strategies might develop at different rates in different individuals, leading to low consistency in individual differences in overall task performance.

As a limitation of our study, we should note that our results are based on correlations and, as such, do not allow us to establish whether the skills that we assessed played a causal role in the development of mathematical skills. Further research could involve specific interventions to improve some of these skills, and check if this leads to improvements in mathematical ability. Future studies could also investigate the stability of these skills over a longer period of time by tracking children throughout the primary school years.

In summary, the current results suggest that some nonnumerical abilities are powerful and reliable predictors of early formal numerical skills. In particular, we found evidence for the important role of ordering skills (see also O'Connor et al., 2018). Nevertheless, future studies could also consider the role of some other nonnumerical skills which develop at an early age.

NOTE

1 The children in the current study were the same as in O'Connor et al. (2018) and some results regarding those children's performance at T1 are also reported in that paper.

REFERENCES

Attout, L., & Majerus, S. (2015). Working memory deficits in developmental dyscalculia: The importance of serial order. *Child Neuropsychology*, *21*, 432–450.

Attout, L., & Majerus, S. (2018). Serial order working memory and numerical ordinal processing share common processes and predict arithmetic abilities. *British Journal of Developmental Psychology*, *36*, 285–298.

Attout, L., Noël, M. P., & Majerus, S. (2014). The relationship between working memory for serial order and numerical development: A longitudinal study. *Developmental Psychology*, *50*, 1667–1679.

Barth, H., Beckmann, L., & Spelke, E. S. (2008). Nonsymbolic, approximate arithmetic in children: Abstract addition prior to instruction. *Developmental Psychology*, *44*, 1466–1477.

Barth, H., La Mont, K., Lipton, J., & Spelke, E. S. (2005). Abstract number and arithmetic in preschool children. *Proceedings* *of the National Academy of Sciences of the United States of America*, *102*, 14116–14121.

Berteletti, I., Lucangeli, D., Piazza, M., Dehaene, S., & Zorzi, M. (2010). Numerical estimation in preschoolers. *Developmental Psychology*, *46*, 545–551.

Bonato, M., Zorzi, M., & Umiltà, C. (2012). When time is space: Evidence for a mental time line. *Neuroscience and Biobehavioral Reviews*, *36*, 2257–2273.

Chen, Q., & Li, J. (2014). Association between individual differences in non-symbolic number acuity and math performance: A meta-analysis. *Acta Psychologica*, *148*, 163–172.

De Smedt, B., Noël, M. P., Gilmore, C., & Ansari, D. (2013). How do symbolic and non-symbolic numerical magnitude processing skills relate to individual differences in children's mathematical skills? A review of evidence from brain and behavior. *Trends in Neuroscience and Education*, *2*, 48–55.

Deary, I. J., Strand, S., Smith, P., & Fernandes, C. (2007). Intelligence and educational achievement. *Intelligence*, *35*, 13–21.

Eurydice at NFER. (2012). *National Foundation for Educational Research: Compulsory age of starting school in European countries*. Retrieved from https://www.nfer.ac.uk/nfer/eurydice/publications/compulsory-ageof-starting-school.cfm

Fazio, L. K., Bailey, D. H., Thompson, C. A., & Siegler, R. S. (2014). Relations of different types of numerical magnitude representations to each other and to mathematics achievement. *Journal of Experimental Child Psychology*, *123*, 53–72.

Friedman, W. J. (1977). The development of children's knowledge of cyclic aspects of time. *Child Development*, *48*, 1593–1599.

Friedman, W. J. (1990). Children's representations of the pattern of daily activities. *Child Development*, *61*, 1399–1412.

Fuhs, M. W., & McNeil, N. M. (2013). ANS acuity and mathematics ability in preschoolers from low-income homes: Contributions of inhibitory control. *Developmental Science*, *16*, 136–148.

Geary, D. C., Brown, S. C., & Samaranayake, V. A. (1991). Cognitive addition: A short longitudinal study of strategy choice and speed-of-processing differences in normal and mathematically disabled children. *Developmental Psychology*, *27*, 787–797.

Gelman, R., & Gallistel, C. R. (1978) *The child's understanding of number*. Washington, DC: American Psychological Association.

Gilmore, C., Attridge, N., Clayton, S., Cragg, L., Johnson, S., Marlow, N., … Inglis, M. (2013). Individual differences in inhibitory control, not non-verbal number acuity, correlate with mathematics achievement. *PLoS One*, *8*, e67374.

Gilmore, C., Attridge, N., De Smedt, B., & Inglis, M. (2014). Measuring the approximate number system in children: Exploring the relationships among different tasks. *Learning and Individual Differences*, *29*, 50–58.

Gilmore, C. K., McCarthy, S. E., & Spelke, E. S. (2010). Non-symbolic arithmetic abilities and mathematics achievement in the first year of formal schooling. *Cognition*, *115*, 394–406.

Halberda, J., Mazzocco, M. M., & Feigenson, L. (2008). Individual differences in nonverbal number acuity predict maths achievement. *Nature*, *455*, 665–668.

Holloway, I. D., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: The distance effect and children's mathematical competence. *Journal of Experimental Child Psychology*, *103*, 17–29.

Inglis, M., & Gilmore, C. (2013). Sampling from the mental number line: How are approximate number system representations formed? *Cognition*, *129*, 63–69.

Inglis, M., & Gilmore, C. (2014). Indexing the approximate number system. *Acta Psychologica*, *145*, 147–155.

Kaufmann, L., Vogel, S. E., Starke, M., Kremser, C., & Schocke, M. (2009). Numerical and non-numerical ordinality processing in children with and without developmental dyscalculia: Evidence from fMRI. *Cognitive Development*, *24*, 486–494.

Lemaire, P., & Siegler, R. S. (1995). Four aspects of strategic change: Contributions to children's learning of multiplication. *Journal of Experimental Psychology: General*, *124*, 83–97.

Li, Y., Zhang, M., Chen, Y., Zhu, X., Deng, Z., & Yan, S. (2017). Children's non-symbolic, symbolic addition and their mapping capacity at 4–7 years old. *Frontiers in Psychology*, *8*, 1203.

Link, T., Huber, S., Nuerk, H. C., & Moeller, K. (2014). Unbounding the mental number line—New evidence on children's spatial representation of numbers. *Frontiers in Psychology*, *4*, 1–11.

Lyons, I. M., Price, G. R., Vaessen, A., Blomert, L., & Ansari, D. (2014). Numerical predictors of arithmetic success in Grades 1–6. *Developmental Science*, *17*, 714–726.

Majerus, S., Poncelet, M., Greffe, C., & Van der Linden, M. (2006). Relations between vocabulary development and verbal short-term memory: The relative importance of short-term memory for serial order and item information. *Journal of Experimental Child Psychology*, *93*, 95–119.

Maloney, E. A., Risko, E. F., Preston, F., Ansari, D., & Fugelsang, J. (2010). Challenging the reliability and validity of cognitive measures: The case of the numerical distance effect. *Acta Psychologica*, *134*, 154–161.

Morsanyi, K., O'Mahony, E., & McCormack, T. (2017). Number comparison and number ordering as predictors of arithmetic performance in adults: Exploring the link between the two skills, and investigating the question of domain-specificity. *Quarterly Journal of Experimental Psychology*, *70*, 2497–2517.

Morsanyi, K., van Bers, B. M., McCormack, T., & McGourty, J. (2018). The prevalence of specific learning disorder in mathematics and comorbidity with other developmental disorders in primary school-age children. *British Journal of Psychology*, *109*, 917–940.

Morsanyi, K., van Bers, B. M., O'Connor, P. A., & McCormack, T. (2018). Developmental dyscalculia is characterized by order processing deficits: Evidence from numerical and non-numerical ordering tasks. *Developmental Neuropsychology*, *43*, 595–621. https://doi.org/10.1080/87565641.2018.1502294

Moyer, R. S., & Landauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature*, *215*, 1519–1520.

Northern Ireland Statistics and Research Agency. (2010, February). *Northern Ireland multiple deprivation measure 2010*. Retrieved 4 January, 2019, from http://www.nisra.gov.uk/deprivation/archive/Updateof2005Measures/NIMDM_2010_Blueprint_Document.pdf

O'Connor, P. A., Morsanyi, K., & McCormack, T. (2018). Young children's non-numerical ordering ability at the start of formal education longitudinally predicts their symbolic number skills and academic achievement in maths. *Developmental Science*, *21*, e12645.

Piazza, M., Facoetti, A., Trussardi, A. N., Berteletti, I., Conte, S., Lucangeli, D., … Zorzi, M. (2010). Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. *Cognition*, *116*, 33–41.

Price, G. R., Palmer, D., Battista, C., & Ansari, D. (2012). Nonsymbolic numerical magnitude comparison: Reliability and validity of different task variants and outcome measures, and their relationship to arithmetic achievement in adults. *Acta Psychologica*, *140*, 50–57.

Reeve, R., Reynolds, F., Humberstone, J., & Butterworth, B. (2012). Stability and change in markers of core numerical competencies. *Journal of Experimental Psychology: General*, *141*, 649–666.

Roth, B., Becker, N., Romeyke, S., Schäfer, S., Domnick, F., & Spinath, F. M. (2015). Intelligence and school grades: A meta-analysis. *Intelligence*, *53*, 118–137.

Rousselle, L., Palmers, E., & Noël, M. P. (2004). Magnitude comparison in preschoolers: What counts? Influence of perceptual variables. *Journal of Experimental Child Psychology*, *87*, 57–84.

Sasanguie, D., De Smedt, B., & Reynvoet, B. (2017). Evidence for distinct magnitude systems for symbolic and non-symbolic number. *Psychological Research*, *81*, 231–242.

Sasanguie, D., & Vos, H. (2018). About why there is a shift from magnitude to ordinal processing in the association with arithmetic between first and second grade. *Developmental Science*, *21*, e12653. https://doi.org/10.1111/desc.12653

Sattler, J. M., & Dumont, R. (2004) *Assessment of children: WISC-IV and WPPSI-III supplement*. San Diego, CA: Jerome M. Sattler.

Schneider, M., Beeres, K., Coban, L., Merz, S., Schmidt, S., Stricker, J., & De Smedt, B. (2017). Associations of non-symbolic and symbolic numerical magnitude processing with mathematical competence: A meta-analysis. *Developmental Science*, *20*, e12372.

Schneider, M., Merz, S., Stricker, J., De Smedt, B., Torbeyns, J., Verschaffel, L., & Luwel, K. (2018). Associations of number line estimation with mathematical competence: A meta-analysis. *Child Development*, *89*, 1467–1484. https://doi.org/10.1111/cdev.13068

Siegler, R. S., & Booth, J. L. (2004). Development of numerical estimation in young children. *Child Development*, *75*, 428–444.

Siegler, R. S., & Opfer, J. E. (2003). The development of numerical estimation evidence for multiple representations of numerical quantity. *Psychological Science*, *14*, 237–250.

Soltész, F., Szűcs, D., & Szűcs, L. (2010). Relationships between magnitude representation, counting and memory in 4- to 7-year-old children: A developmental study. *Behavioral and Brain Functions*, *6*(1), 13.

Strenze, T. (2007). Intelligence and socioeconomic success: A meta-analytic review of longitudinal research. *Intelligence*, *35*, 401–426.

Vos, H., Sasanguie, D., Gevers, W., & Reynvoet, B. (2017). The role of general and number-specific order processing in adults' arithmetic performance. *Journal of Cognitive Psychology*, *29*, 1–14.

Wechsler, D. (2003) *Wechsler preschool and primary scale of intelligence—Third UK edition (WPPSI-III)*. Oxford, England: Psychological Corporation.

Wong, T. T. Y., Ho, C. S. H., & Tang, J. (2016). The relation between ANS and symbolic arithmetic skills: The mediating role of number-numerosity mappings. *Contemporary Educational Psychology*, *46*, 208–217.

Xenidou-Dervou, I., De Smedt, B., van der Schoot, M., & van Lieshout, E. C. (2013). Individual differences in kindergarten math achievement: The integrative roles of approximation skills and working memory. *Learning and Individual Differences*, *28*, 119–129.

Xenidou-Dervou, I., Molenaar, D., Ansari, D., van der Schoot, M., & van Lieshout, E. C. (2017). Non-symbolic and symbolic magnitude comparison skills as longitudinal predictors of mathematical achievement. *Learning and Instruction*, *50*, 1–13.